A BUSINESS CASE FOR SPACE DEBRIS

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To support a pleasant reading experience, footnotes and references will use the same numbering, but can refer to dissimilar sources. The footnotes at the bottom of the pages are implemented as hyperlinks that refer to short online articles to quickly validate the statements. Relevant online sources will be made available as a copy at the end of the reference list (as of 27.07.2021). The references at the end of the document refer to additional studies, scientific papers, or books for further readings.

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STUDY MOTIVATION

Space debris is a fundamental problem. Since the launch of Sputnik 1 in 1957, thousands of defective objects have remained in space.[1] Due to new "mega-constellations" such as *Starlink* for satellite broadband and others, this number is growing exponentially. This increases the risk of collisions and even more space debris.[2]

As more and more areas of modern life depend on functional space services,[3] such as navigation services such as *Galileo* or the Earth observation program *Copernicus*, a service failure due to a collision in space would cost much more than "just" the replacement of a satellite.[4] The *Organisation for Economic Co-operation and Development (OECD)* recently published its first report on the economic cost of space debris,[5] stating *"Space debris protection and mitigation measures are already costly to satellite operators, but the main risks and costs lie in the future, if the generation of debris spins out of control and renders certain orbits unusable for human activities."*

The most effective way to stabilize the debris population is to actively remove large non-functional objects from the most populated orbits.[6] This has been shown in analyses by NASA and ESA and several *Active Debris Removal* (ADR) technology assessment studies have been conducted in the past.[7]

Unfortunately, funding ADR missions has been (and still is!) a challenge. This underlines the remark made by the former Director General of ESA at the 2015 Paris Air Show that it is difficult to get member states to pay for "waste removal" as it is typically "*…far more interesting to give contribution to an interplanetary probe"*.[8]

The ESA Council at Ministerial Level, *Space19+*, has finally agreed to a first ADR mission, *ClearSpace-1*, which was procured by ESA as a service contract with a planned launch in 2025.[9] But while *ClearSpace-1* is a first step in the right direction, funding for the following ADR missions remains unclear: Who should pay for such a service if there is no legal obligation for a space debris owner to actively remove it?[10]

This study, conducted by Frank Koch - Orbit Recycling, addresses the challenges of such an ADR mission. Instead of relying solely on the "*noble cause of space debris removal*",[11] it shows a new business opportunity by highlighting the value of space debris: its recycling potential. On Earth, this potential is already fully recognized. The German recycling industry alone generates more revenue[12] than the entire European space industry[13]. Nevertheless, this treasure was never lifted in space.

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[1] Space Environment Report- ESA
[2] Effect of Mega-Constellations on Collision Risk in Space
[3] Impact of Space activities upon society report - ESA
[4] The cost of space debris - ESA
[5] Space Sustainability - OECD
[6] Active Debris Removal - ESA
[7] E.G., e.deorbit CDF Study: A Design Study for the Safe removal of Large Space Debris - ESA
[8] ESA e.deorbit – ESA's Active Debris Removal Mission (5.2) - ESA
[9] The ClearSpace-1 mission: ESA and ClearSpace team up to remove debris
[10] Industrial commitments on legal aspects of active debris removal - Space Legal Issues
[11] ESA e.deorbit – ESA's Active Debris Removal Mission (5.2) - ESA
[12] Waste Management & Recycling in Germany 2020 - Statista
[13] European Space Industry Turnover 2010-2019 - Statista

In summary, the identified use case with the greatest potential for Europe is shown in Figure 1. By tugging old Ariane upper stages from their current positions further to the Moon, dozens of tonnes of aluminium could be recovered and recycled. The aluminium could e.g., act as building material on the Moon. Since space agencies around the world expressed their interests in a lunar ground station in the *Global Exploration Roadmap* (GER),[14] the demand for construction material is given. Supply through this recycling approach would avoid costly material transports from Earth and could act as an interim solution until lunar *In-Situ-Resource-Utilization* (ISRU) technology becomes fully available in the future.[15]

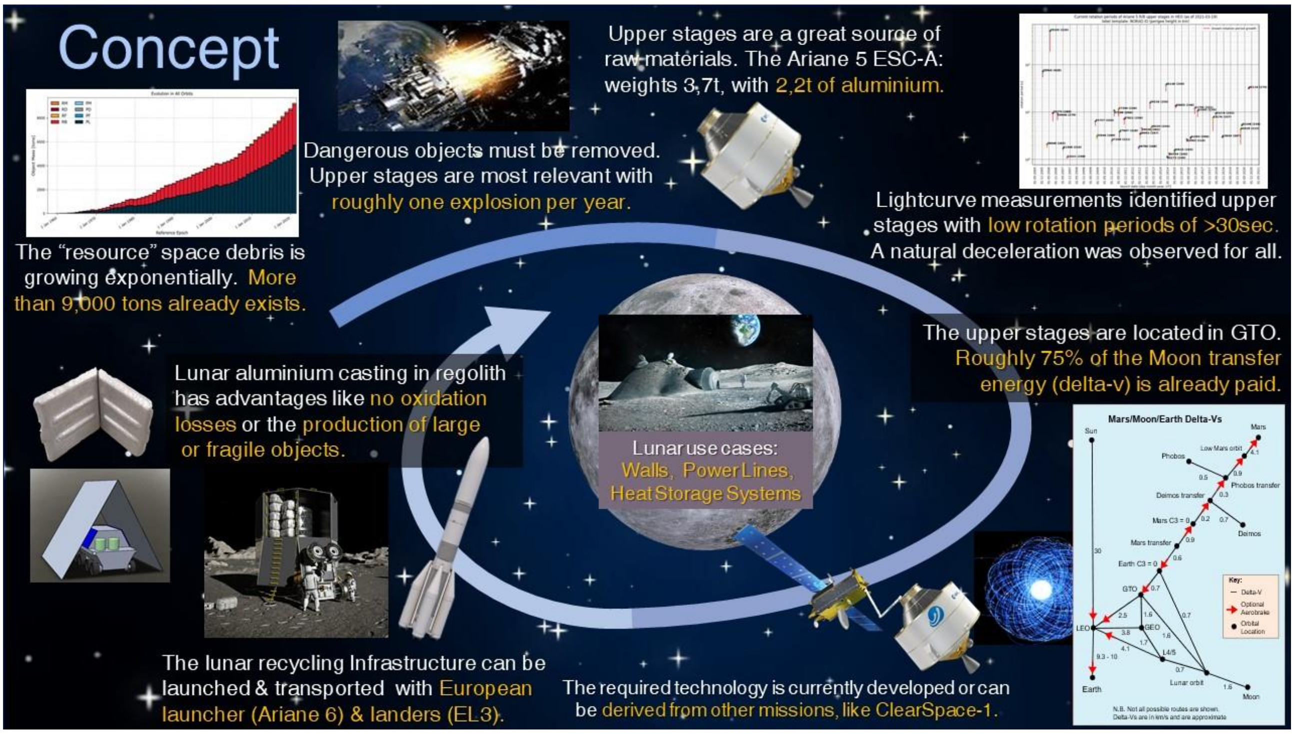

Figure 1: Space Debris Recycling (Orbit Recycling)

Although this concept sounds futuristic, the study concludes that it is within Europe`s current capabilities. The necessary technology can be derived from existing ESA development programs and allows the involvement of all ESA member states. The space industry could refinance the cost of the recycling mission by selling the raw material on the Moon or by allowing ESA to use the raw material as "barter goods" with other space agencies, e.g., for lunar ESA astronaut missions.

In terms of content, the first part of the study begins with a brief overview of the problem of space debris and discusses the identified recycling potential. The second part deals with relevant technology aspects and highlights synergies with existing (research) activities of ESA and its industrial partners. The third part calculates the business case and compares relevant alternatives.

Where appropriate, the study proposes complementary research and follow-up measures to close identified knowledge gaps.

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[14] Global Exploration Roadmap Supplement – Lunar Surface Exploration Scenario Update, Chapter 4 - ISECG

[15] ESA Space Resources Strategy - ESA

PART 1

Introduction to Recycling

INTRODUCTION

THE PROBLEM OF SPACE DEBRIS

CHAPTER SUMMARY

The following theses about space debris are postulated and substantiated in this chapter:

T-SD-1	Space debris endangers all space activities due to uncontrollable collision risks.
T-SD-2	The amount of space debris is growing.
T-SD-3	Funding of ADR missions remains challenging.

By comparing the space situation with Earth, the following conclusions are derived from the theses:

C-SD-1	Like on Earth, Active Debris Removal (ADR) is needed to reduce or to stabilize the quantity of debris.	T-SD-1 T-SD-2
C-SD-2	Like on Earth, recycling might be a financing option for waste treatment in space.	T-SD-3
C-SD-3	Like on Earth, a better understanding of the debris composition is needed to allow ADR missions as well as recycling of debris.	C-SD-1 C-SD-2

Within the space sector, the problem of space debris is well understood. ESA`s *Annual Space Environment Report*[16] regularly reviews the latest figures and trends. A simplified summary would be, that the amount of space debris is steadily increasing. This growth of space debris endangers all kinds of space activities through collisions with uncontrolled objects, causing even more debris. This cascading effect, which could end in unusable orbits, is called *Kessler syndrome.*[17]

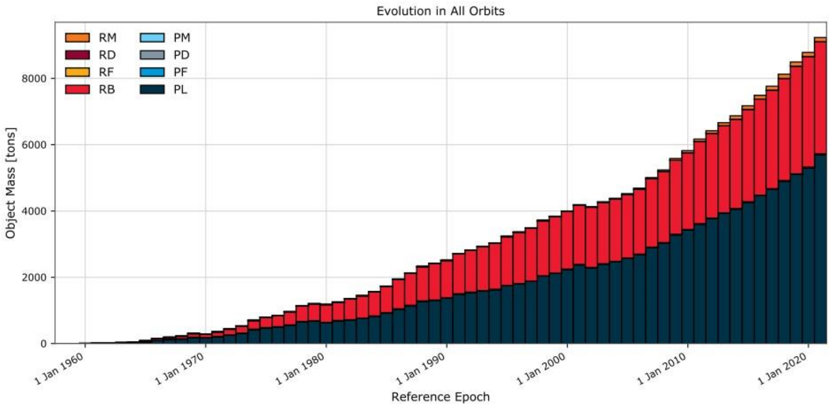

Figure 2: Exponential Growth of Space Debris (ESA, (16))

To stabilize the number of space debris, it is important to actively remove at least all future space objects from the orbits. Ideally, this happens automatically at the end of each mission. According to the *Mitigation Guidelines*[18] of the *Inter-Agency Space Debris Coordination Committee* (IADC), a grouping comprising ESA and 10 national space agencies, spacecraft in *Low Earth Orbits* (LEO) should be deorbited, i.e., fall into the

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[16] Space Environment Report- ESA

[17] Collision Frequency of Artificial Satellites: The Creation of a Debris Belt

[18] Mitigation Guidelines rev.1 Sep.2007, Chapter 5.3.2 - IADC

atmosphere and "burn", within 25 years of the mission's ending, while objects in *Geostationary Orbits* (GEO) are elevated to at least 300 km above the geosynchronous orbital ring and parked in a "*graveyard orbit*". Similar guidelines have been taken up by the *United Nations Office for Outer Space Affairs* (UNOOSA).[19]

However, to be able to address existing objects, a better understanding of the current situation is required. An important European data source for such an analysis is DISCOS (*Database and Information System Characterising Objects in Space*).[20] So far, the data collection is driven by collision risk and re-entry predictions and usually contains public information about the details of the object registration, descriptions of the launch vehicle, as well as spacecraft information (e.g., size, mass, shape, mission objectives, owner). Unfortunately, DISCOS do not include the composition of the object itself, such as what material in what percentage or type of components were used to create the object. Such information would be relevant for waste treatment activities such as recycling.

Today, recycling is one of the most sought-after treatments of terrestrial waste. In the European Union, waste management is based on the "waste hierarchy", which establishes the following priority order at operational level: prevention, reuse, recycling, recovery, and disposal as the least preferred option.[21] However, recycling only works properly if the recycler knows which material or object to look out for. One of the main obstacles of the so-called "*landfill mining and reclamation* (LFMR)" is the difficulty of understanding the composition of the landfilled waste.[22] Records for many older landfills do not exist or are incomplete. If the waste composition is not well understood, the project may be too risky, and costs cannot be scoped appropriately.

The same applies to space: without knowing the material and component composition of an object, a serious assessment of the treatment and recycling potential of the object remains a challenge. For certain objects or certain object classes in space, unofficially good-enough-estimates of the quantities of material used are available. Although not in detail, space experts and enthusiasts around the world have collected, peer-reviewed and published such information. This includes detailed data on all kind of launcher stages, available through websites such as *Wikipedia*[23] or *Bernd Leitenberger*`s private website.[24]

RECOMMENDED NEXT STEPS

Official space debris data sets such as DISCOS should be expanded to include object material information to support future waste management activities such as the removal of space debris or recycling. On Earth, this lack of information hinders the efficient treatment of old landfills. In space, similar problems will occur when debris is treated one day in the future.

Since space objects are usually extensively reviewed and tested in advance by various authorities, such information is available. Space agencies such as ESA should consider whether it would be possible to extend DISCOS or similar data sets to include the material information of space objects. If necessary, the information

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[19] Mitigation Guidelines, Guideline 6 - UNOOSA
[20] DISCOS - ESA
[21] Waste Environment - European Commission
[22] Landfill Mining: Goldmine or Minefield? - Waste Management World
[23] Overview of launch vehicles - Wikipedia
[24] Oberstufen (upper stages) - Bernd Leitenberger (in German)

can be encrypted and kept secret until it is needed in the future. The costs of such an extension could be (partially) refinanced by making this information available to waste treatment companies as a paid service in the future.

INTRODUCTION TO RECYCLING

CHAPTER SUMMARY

The following theses about recycling are postulated and substantiated in this chapter:

T-RE-1	Recycling is driven by political decisions or financial benefits.
T-RE-2	Recycling can be separated in life cycle extension, reuse of components or material recycling.
T-RE-3	Terrestrial recycling works best for certain raw materials like metal.

By comparing the space situation with Earth, the following conclusions are derived from the theses:

C-RE-1	Like on Earth, the right political decisions could boost a sustainable space recycling industry.	T-RE-1
C-RE-2	Like on Earth, due to technical limitations, recycling is not the answer for every kind of debris.	T-RE-2 T-RE-3

This study deals with the topic of space debris recycling. It is neither about the aspect of "reusable" launchers such as SpaceX with its reusable Falcon 9[25] or its upcoming Starship[26], nor about reusable spaceships such as the former US Space Shuttle[27] or the upcoming European Space Rider[28]. While these concepts have reusability in mind and avoid the formation of space debris, they neither address nor reduce the number of debris present. Nevertheless, these examples show how financially attractive reusability in the space industry could be, if it is part of the original design criteria.[29]

In general, recycling of waste is defined "*as any recovery operation by which waste materials are reprocessed into products, materials, or substances whether for the original or other purposes*".[30] It does not include energy recovery and reprocessing into materials to be used as fuels or for backfilling. However, in space, the use of waste as fuel may be relevant, and therefore this case is included.

The terms *reuse*, *recycling* and *recovery* have clear definitions, e.g., described in the *EU Waste Framework Directive*.[31] Since this study is aimed at experts in the non-recycling industry, but of the space industry, in this study the word "*recycling*" is used in its mutual understanding as a synonym for various activities, including:

- Life cycle extension (extension of the useful life of a functional object),
- Reuse of (working) components as part of a new object as well as
- Recycling of raw materials of debris for the construction of other objects or as fuel.

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[25] Falcon-9 - SpaceX
[26] Starship - SpaceX
[27] Shuttle Era Facts - NASA
[28] Space Rider Factsheet - ESA
[29] SpaceX Economics - Inverse.com
[30] Glossary: Recycling of waste - European Commission
[31] EU Waste Framework Directive - European Commission

RECYCLING ON EARTH

In recent decades, the returns from recycling have been considerable and have grown rapidly. Between 2004 and 2008, the turnover of seven main categories of recyclables in the EU almost doubled to more than EUR 60 billion. The highest recycling rates are achieved for raw materials (especially ferrous metals and aluminium). [32]

Recycling is driven either by political decisions or by economic reasons. Aluminium, which is relevant to the space industry, is a good example. The highest cost factor for aluminium is the production energy: It takes 12 to 17 kw/h to produce a kilogram of primary aluminium, but it takes only 5% of this energy to recycle 1kg of aluminium. Depending on the sector, Europe achieves aluminium recycling rates of between 75% and 90%. And thanks to recycling, Europe, with its lack of own resources, is becoming more independent in its supply.[33]

But not everything is suitable for recycling. A UN study found that only 20% out of 50 million tonnes of e-waste are formally recycled,[34] mainly because the recycling processes are too complex and /or too expensive.[35] In general, extending the life cycle is a better way to address the problem of e-waste.[36]

RECYCLING IN SPACE

Recycling in space would be driven for the same reasons as on Earth: politically and / or economically. While the EU has a clear commitment to environmental protection, which is expressed in the European Commission's *Green Deal*,[37] space protection is not explicitly mentioned. On the ESA side, the *ESA Clean Space Initiative* has systematically considered the entire life cycle of space activities, from the preliminary phase of conceptual design to the end of the mission, including the removal of space debris,[38] although again, it does not mention recycling. A clear political statement for the recycling of space debris is missing.

From an economic perspective, space debris has a total recycling potential of more than 9,000 tons,[39] which is only a tiny fraction of the 2,317 million tonnes of waste produced in Europe in 2018.[40] These +9,000 tonnes are very divers,[41] ranging from the "school bus sized" satellite *Envisat*[42] via old rocket upper stages down to small explosion fragments, solid rocket motor slag or NaK droplets from nuclear reactors and the like.[43] And as on Earth, different types of debris would require different recycling technologies and processes, further reduces the scaling effects for space debris.

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[32] Recycling industry can boost the European economy — European Environment Agency
[33] Circular Aluminium Action Plan - European Aluminium
[34] Challenge E-Waste - UN
[35] E-Waste Recycling, The e-waste recycling process - Recycling Inside
[36] Electrical and electronic waste - Umweltbundesamt, Germany
[37] A European Green Deal - European Commission
[38] Space Debris: The Challenge - ESA
[39] About Space Debris - ESA
[40] Waste statistics - European Commission
[41] About Space Debris - ESA
[42] New Envisat Infographic - ESA
[43] A Model of the Space Debris Environment - Joint Air Power Competence Centre

Another key difference between terrestrial waste and space debris is the required "collecting effort". Usually, terrestrial waste is lying on the ground or is collected in a trash can, which facilitates its disposal. In space, the debris moves at high speeds of about 10 km/s.[44] Objects larger than a millimetre could already damage spaceship structures, while objects larger than 10cm can destroy them.

The high speeds, combined with small object sizes, make it hardly possible to attach and capture slags, droplets, and similar fragments with today's technology; in addition to the fact that there is no waste treatment concept for these materials in low or zero gravity. Therefore, this study focuses on the few thousand satellites and rocket upper stages that are large enough to take care of them today. While this is only a tiny fraction of the hundreds of thousands of objects in space, it is still most of the total mass of debris in orbit.

However, this amount of waste, with its limited number of identical objects, requires different treatment methods than waste treatment on Earth. First, collecting, and dismantling objects in space will be complex, as this is still mainly a manual process on Earth.[45]

One reason, why recycling space debris would still make financially sense is that it could avoid, or at least drastically reduce launch costs, since the debris is already in space. Depending on the orbit height, several thousand euro per kilogram material are charged for a lift,[46] which is more expensive than each material itself. Since the launch costs have already been paid by the primary lift-off, avoiding, or at least reducing these costs makes recycling in space financially attractive. All it needs is to find the right balance between the total recycling costs and the reduced launch costs.

RECOMMENDED NEXT STEPS

Without a clear political commitment, the recycling activities for space debris will remain a challenge, regardless of any potential economic benefit. ESA`s previous Council at Ministerial Level, Space19+, has pledged a first ADR mission, *ClearSpace-1*, which was procured by ESA as a service contract with a planned launch in 2025.[47]

While *ClearSpace-1* is a first step in the right direction, funding for subsequent ADR missions remains unclear. With the financial benefits of a space debris recycling concept, a successful *ClearSpace-1* mission could free up additional public budgets for future ADR missions if prepared well enough in advance. If ESA sees benefits in such activities, this issue should be put on the agenda of the next ESA Council at Ministerial Level.

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[44] Collision Velocity in LEO - Spaceacademy.net

[45] The World Has an E-Waste Problem - Time Magazine

[46] Overview Commercial Launch Costs 2017, p. 22 + p.30 - US GAO

[47] ESA commissions world's first space debris removal - ESA

RECYCLING OPPORTUNITIES IN SPACE

Different recycling options for larger objects in space can be categorized in the following three use cases, which will be explained in the next chapters:

- Life cycle extension
- Reuse of working components
- (Raw) material recycling

LIFE CYCLE EXTENSION

CHAPTER SUMMARY

The following theses about life cycle extension (LCE) are postulated and substantiated in this chapter:

T-LCE-1	Life Cycle Extension (LCE) is proven in space.
T-LCE-2	Costs for LCE competes with costs for “space object replacement” (object successor).

By comparing the space situation with Earth, the following conclusions are derived from the theses:

C-LCE-1	LCE needs to be included already in the design phase.	T-LCE-1
C-LCE-2	Without standardization, LCE is financially not attractive as no scaling effects could be realized.	T-LCE-1 T-LCE-2
C-LCE-3	LCE in space is mostly interesting for objects with high launch costs, like heavier objects or objects in higher orbits.	T-LCE-1 T-LCE-2

Life cycle extension is not new to space. Well-known examples are the *Hubble Space Telescope* (Hubble) and the *International Space Station* (ISS). What both have in common is that a life cycle extension has been included in advance in their designs. *Hubble* is the only telescope to be maintained by astronauts in space. Five Space Shuttle missions have repaired, upgraded, and replaced systems at the telescope, including all five main instruments.[48] On the other hand, the ISS was not only built over several missions in space, but still receives external support including the raise of orbits as well as functional enhancements and extensions.[49] The life cycle of the ISS has only recently been extended until 2028.

Figure 3 Artist's view of the Shuttle servicing mission of Hubble (ESA)

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[48] Hubble Servicing Missions - NASA

[49] Space Station Assembly - NASA

The decision to include life cycle extension directly into the design can be explained by the initial inflated costs and heavy weights for Hubble as well as for the ISS, which made life cycle extension through service missions cheaper than launching a replacement for them. However, if a space object were not designed for life cycle extension, such a service mission would be an overly complex challenge and not always possible.

So far, there is no standardization in interfaces, neither for safe approach to an object nor for maintenance, such as refuelling or external orbit changes. In 2011, a first concept of a generic *satellite refuelling spacecraft* was developed, which eventually led to the *Mission Extension Vehicle* (*MEV*), now operated by Northrop Grumman.[50] *MEV-1* was launched in 2019 and docked and repositioned Intelsat IS-901 in April 2020. A second mission, *MEV-2*, has dock with Intelsat IS1002 in early 2021. Both *MEV* missions are aimed at heavy telecommunication satellites in the high *Geostationary Orbit* (GEO), which ran out of fuel and were therefore no longer able to maintain their orbital positions. The *MEV* has its own thrusters and operates independently of the target, while being continuously connected to it. It is expected that *MEV-1* and *-2* will be able to keep their target satellites in place for the next five years to maintain their services.

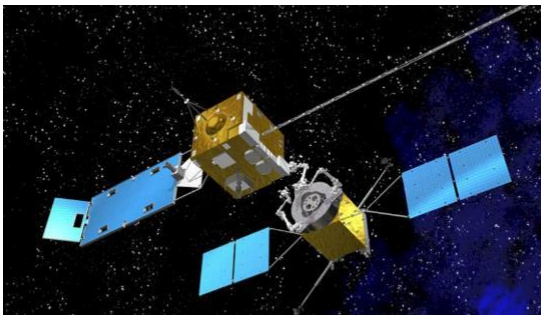

Figure 4 Artist`s view of the Northrop Grumman *MEV* (Northrop Grumman)

Since most GEO satellites are derived from a few satellite busses, the *MEV*s will be able to serve a significant percentage of the telecommunications satellites in GEO. The *MEV*s could be rededicated after their first missions and then serve more satellites. Compared to the satellite exchange of a telecommunication satellite in GEO, the total mission costs are therefore in an “acceptable range”, which makes the *MEV* a good showcase for space recycling through life cycle extension.[51]

But the *MEV* has no refuelling or component replacement capabilities. The *MEV* shall refer to the target satellite throughout the period of service extension. The degradation of components due to the harsh space conditions will limit the total lifetime of the GEO satellite; and in the event of a component failure, the *MEV* would not be able to address this different situation, which would lead to a loss of the satellite. The same goes for the *MEV* itself; a component failure of the *MEV* over its own lifetime in space would lead to the loss of both, the *MEV* and the connected satellite.

On the other hand, thanks to its own propulsion system, the *MEV* could tackle partial launch failures, in which satellites get stuck in lower or so-called *transfer orbits*. The *MEV* could raise the satellite into its desired orbit without using the satellite`s fuel, which would help extend the life cycle of the satellite. Similar service concepts are currently planned by other companies, such as *Momentus* from the US.[52]

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[50] Space Logistics Services - Northrop Grumman

[51] MEV-1: A Look Back at Intelsat’s Groundbreaking Journey - Intelsat

[52] Services - Momentus

SITUATION IN LEO

Unfortunately, the situation in LEO is quite different. Satellites in LEO are derived from a variety of satellite busses. Usually, they are much lighter and cheaper than GEO satellites and could be launched at much lower cost.[53] Launching a replacement satellite will often be more financially attractive than a costly life cycle extension mission, that will also have to be launched in LEO. In addition, a newer replacement satellite could benefit from technological improvements and upgrades, allowing it to offer better or more reliable services than the outdated one.

Good examples of this LEO dilemma are mega constellations. Instead of life cycle extension designed in, they have failure rates designed in for their services: a certain percentage of the satellites could fail without service degradation.[54] Since some of these mega constellations operate in orbits above 800km,[55] where atmospheric air resistance is too small to deorbit (old) objects naturally, this “throwaway” mentality is even worse, but much more attractive from a financial point of view.

Figure 5 Artist`s view of a Satellite Mega Constellation

This could change in the future with greater standardization in the refuelling of satellites or the replacement of components. If satellites could be easily refilled in LEO, their lifetime could be extended, resulting in fewer satellite launches and thus less space debris. The same applies if a failed component such as a solar panel or an antenna could be replaced without much effort and associated risks by a service mission, which will be discussed in more detail in the next chapter. Although such standards still do not exist, there are currently several independent commercial solutions that have been developed to address this problem. Few examples of this are listed below:

- The aforementioned company *Momentus* is developing its own satellite platform that can be refuelled and maintained by the *Momentus service fleet* in space. Along with launch, orbit raising, refuelling and maintenance subscriptions, the platform will be offered to customers for their own space missions.
- *Astroscale* from Japan is working on a docking plate for satellite busses, that allows easy docking. Together with *Astroscale`s* upcoming own space servicing vehicle, *Astroscale* would offer all customers an end-of-life removal service with the docking plate.[56] The same technology could be used to re-obit a customer`s satellite if desired, turning this solution into a specialized life cycle extension offering for LEO. Over time, *Astroscale* also wants to offer a scaled solution for GEO missions.

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[53] Small Satellite Market Industry Report -Mordor Intelligence
[54] About 3% of Starlink satellites have failed so far - Phys.org
[55] Satellite constellation, List of satellite Constellations - Wikipedia
[56] End of Life Services - Astroscale

Despite this positive development, LEO could not offer any financial use case for recycling due to the low launch costs. Even the closed-loop support systems of the ISS are currently losing their business case, according to NASA:[57]

"The development of commercial launch vehicles by SpaceX has greatly reduced the cost of launching mass to Low Earth Orbit (LEO). … These ISS regenerative and recycling life support systems have significantly reduced the total launch mass needed for life support. But, since the development cost of recycling systems is much higher than the cost of tanks and canisters, the relative cost savings have been much less than the launch mass savings. … If another space station were built in LEO, resupply life support would be much cheaper than the current recycling systems. "

RECOMMENDED NEXT STEPS

Life cycle extension in space is a proven way to counter the common "throwaway" mentality of space missions, which should lead to less space debris over time. However, due to the lack of standardization, this is often not financially attractive.

ESA should use its influencing capabilities to change this. Under the *Clean Space Initiative*, including *EcoDesign*[58], *CleanSat*[59] and *In-orbit Servicing/Active Debris Removal*[60], ESA could work towards such technical standardization over time. Low-hanging fruits for life cycle extensions could be docking plates or refuelling concepts, while in the medium term replaceable external components such as antennas and solar panels should be normalized. In the long term, internal component replacements of e.g., batteries or *Guidance, Navigation & Control Systems* (GNC) should follow.[61]

As ESA is (at least partly) responsible for the large European satellite fleet of the *Copernicus* and *Galileo* service, it should request the aforementioned capabilities for the next generations of satellites.[62] The larger *Galileo* satellite fleet could benefit from the docking plates and refuelling interfaces, as dozens of them are in high orbits at about 23,200km above Earth and have to be replaced about every twelve years.[63] Here, ESA could act as a best practice for life cycle extension for at least some of the relevant components.[64]

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[57] Much Lower Launch Costs Make Resupply Cheaper than Recycling for Space Life Support - NASA
[58] Ecodesign - ESA
[59] Cleansat - ESA
[60] In-Orbit Servicing / Active Debris Removal - ESA
[61] Guidance, Navigation, and Control (GN&C) - NASA
[62] Evaluation of the debris environment impact of the ESA fleet
[63] Galileo Facts and figures - ESA
[64] Galileo Satellite Anatomy - ESA

REUSE OF COMPONENTS

CHAPTER SUMMARY

The following theses about reuse of components (RoC) are postulated and substantiated in this chapter:

T-RoC-1	Reuse of Components (RoC) is hardly proven in space.
T-RoC-2	Costs for RoC competes with costs for "space object replacement" (object successor).

By comparing the space situation with Earth, the following conclusions are derived from the theses:

C-RoC-1	RoC needs to be included already in the design phase.	T-RoC-1
C-RoC-2	Without standardization, RoC is financially not attractive as no scaling effects could be realized.	T-RoC-1 T-RoC-2
C-RoC-3	RoC in space might be interesting for components with high launch costs, like large antennas or optics or for higher orbits (GEO). Still, hardly any financially attractive use case could be identified.	T-RoC-1 T-RoC-2

In the previous chapter, the aspect of life cycle extension was discussed to solve the problem of space debris. Refuelling or servicing space objects has been done in the past and could become mainstream if this concept is part of the original design. *Hubble* and the *ISS* are examples of such a life cycle extension.

In the recent past, the idea arose to achieve similar benefits by reusing (expensive) components in space. When a space object reaches the end of its lifespan, becomes unusable or un-responding, it usually does not mean that it has completely failed. Often only parts of it died, or the space object simply run out of fuel or batteries. If the object had been designed in advance in such a way that (working) components would be easily accessible or could be dismantled, they could theoretically be reused in other objects instead of becoming space debris.

If the reuse of components (or objects) should be financially attractive, the replacement work in space must be done automatically. Nevertheless, the lack of standardization for the disassembly and replacement of components leads to complex manual processes. In the past, this was done through *extravehicular activities* (EVA) of astronauts.

One example is the recovery of the two satellites *Palapa B2* and *Westar 6*. Both satellites were deployed during the space shuttle mission *STS-41-B* in 1984 but ended up in a wrong orbit due to a component failure.[65] Nine months later, both satellites were recovered on the shuttle mission *STS-51-A* and brought back to Earth.[66] After refurbishment, *Westar 6* was sold and launched back into orbit on April 7, 1990, as *AsiaSat1*.[67]

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[65] STS-41B Mission - NASA

[66] STS-51A Mission - NASA

[67] AsiaSat 1 - Gunter's Space Page

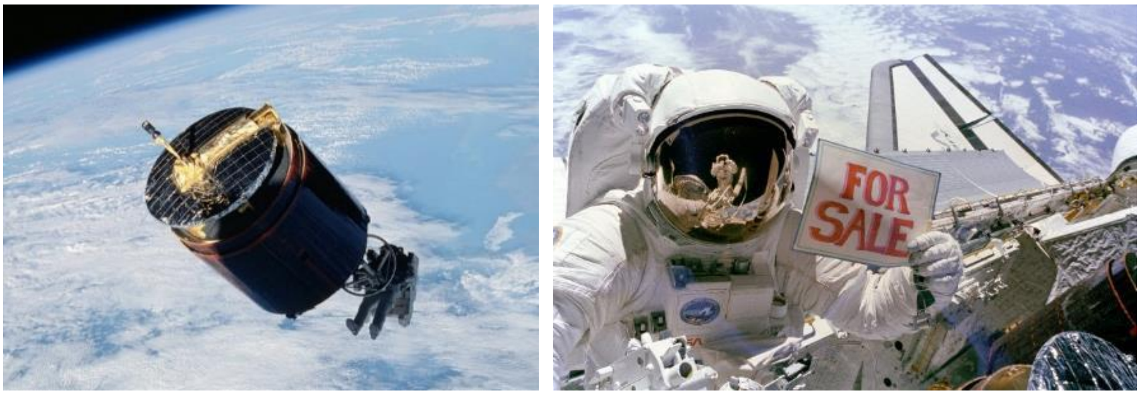

Figure 6 Capturing of the Westar 6 Satellite - Astronaut Dale A. Gardner after retrieving the satellite (NASA)

This case of reusing working components reveals a major problem associated with this concept: it was not financially attractive. As the New York Times reported, satellite insurance Lloyd's paid out $180 million to the original owners in return for the two "malfunctioning" satellites.[68] Lloyd`s hoped to sell both satellites for around $50 million after their terrestrial refurbishment. But with an average (shuttle) mission cost of at least $450 million,[69] the cost of manual labour is not financially justifiable in this way, beside the fact that the shuttle program ended years ago. In addition, the satellites had to be launched into space again at a high price, which makes the entire case financially more than questionable.

Even assuming that components could be automatically dismantled in space in the future, the concept remains questionable: the harsh condition in space usually leads to functional degradation over time, which limits the overall lifespan of the components. Solar panels, for example, can suffer between 1-10% loss of efficiency per year, depending on their coverings.[70] ESA has a good understanding of these degradation effects at different orbital altitudes. Via ESA`s *SPace ENVironment Information System* (SPENVIS)[71] provides free access to various modelling tools and data sets for in-depth research into the calculation of radiation doses, atomic oxygen erosion depths, micrometeoroids, and space debris impact risks.

Especially in LEO, the reuse of older components remains questionable. The risk of severe degradation and an overall reduced lifespan in combination with the additional service mission costs and associated mission risks could not outweigh the low launch costs for new components in LEO. Expensive components such as highly specialized optics, research instruments or uniquely designed antennas could be an exception, although the same argument given in the life cycle extension chapter applies here as well: A newer replacement component could benefit from technological improvements and upgrades, so that it can offer better or more reliable services than the reused one.

In higher orbits, this could be different if the space objects were designed for automated maintenance. One could imagine that a GEO base service fleet, such as the *MEV* concept mentioned above, would approach old satellites, and recover still usable components (or remaining fuel) that would be stored in a space-based "warehouse". If a component failure occurs in another satellites in GEO (or the fuel runs out), the failed component can be replaced by a stock item (or refilled) by a GEO maintenance mission. Such a mission would

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[68] Space Shuttle poised for liftoff... - New York Times
[69] Space Shuttle FAQ, FAQ 10 - NASA
[70] Modeling solar cell degradation in space
[71] SPENVIS (SPace ENVironment Information System) - ESA

be faster than launching a replacement satellite in GEO, which would lead to faster restoration of service. A valid business case would be if the cost of a replacement satellite, its launch in GEO and the longer service outage were higher than the fee for the service mission and the (partial) amount for the GEO service fleet and the space warehouse infrastructure.

RECOMMENDED NEXT STEPS

The recommendations for reusing components in space are like the life cycle extension scenario above: Without further standardization, automated component replacement is not possible and therefore no serious business case is conceivable. But even with the help of future standards, a valid business case for LEO is hard to imagine due to the decreasing satellite and launch costs.[72]

In higher orbits, such a business case could be developed over time with the increasing number of standardized satellite interfaces. Here, too, ESA could drive this development forward by requesting such interfaces for new generation of its *Galileo* satellite fleet. Even if no space warehouses were initiated in the next decades, the implementation of such interfaces would enable a future realization of such a concept. Given the lifetime of GEO satellites of 10-15 years and a remaining time in nearby graveyard orbits of centuries and longer, ESA could set the stage for the reuse of space component now for future generations.

Figure 7 Artist`s view of Galileo satellite fleet (OHB)

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[72] Launch costs to low Earth orbit - Future TimeLine

RAW MATERIAL RECYCLING

CHAPTER SUMMARY

The following theses about raw material recycling (RMR) are postulated and substantiated in this chapter:

T-RMR-1	Raw Material Recycling (RMR) is commodity on Earth but new to space. Still, RMR seems to be realistic for certain space scenarios like metal (aluminium) recycling, especially on the Moon.
T-RMR-2	Costs for RMR competes with costs from Earth materials or with local material alternatives (ISRU).

By comparing the space situation with Earth, the following conclusions are derived from the theses:

C-RMR-1	Terrestrial RMR process technology is mature and proven and could be applied to space with minor adjustments.	T-RMR-1
C-RMR-2	Metal, especially aluminium, seems to be the “sweet spot” for RMR.	T-RMR-1
C-RMR-3	RMR works best for larger objects and objects with a high metal content.	T-RMR-1 T-RMR-2
C-RMR-4	RMR has the highest ROI of all identified recycling use cases.	T-RMR-2
C-RMR-5	The Moon is the financially most attractive recycling spot due to the upcoming metal demand for constructions of the planned Moon station.	T-RMR-2

As already mentioned, the life cycle extension of satellites could be possible in the future with the introduction of increased interface standardization. Larger GEO satellites could be a first target group. In LEO, the greater variety of satellite types can prevent a high standardization rate; and the drastically lower launch costs could prevent the financial motivation for each life cycle extension mission in LEO.

The same is true of component reuse in space: future standardization could make it possible to replace a failed component (which could be considered a life cycle extension) but reusing working parts from a broken satellite in another space object will be complex, costly, and therefore questionable. Again, certain scenarios could only be envisioned for larger GEO satellites, where this could make sense from a financial aspect.

A more realistic scenario should be *raw material recycling*. In Europe, terrestrial recycling of raw materials is quite common. Glass, paper, and metal recycling is well established, a multi-billion-euro-industry[73] and part of the European Commission`s *Raw Material Initiative.*[74] The most interesting for space applications would be metal or aluminium recycling, as shown later in this chapter.

One driver for raw material recycling in space would be *in-space manufacturing.*[75] As early as 1969, the welding of aluminium and other metals in space was tested by Russian cosmonauts. Among others, the *International Space Station* (ISS) was built and assembled in space,[76] although at that time all materials were supplied by Earth. But with companies like *Made in Space*[77], the situation is changing. With the establishment of the first

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[73] Recycling Industry - European Environment Agency

[74] Raw Materials Initiative - European Commission

[75] In Space Manufacturing - NASA

[76] ISS Assembly - NASA

[77] Additive Manufacturing Facility - Made in Space, a Redwire company

commercial 3D printer in space on board of the ISS, additive manufacturing in space became a commodity, with over 200 tools, assets and parts produced in orbit. Currently, only polymers are processed on the ISS, but 3D printing technology can also be used for metals like aluminium alloys in general.[78] As on Earth, the supply of raw materials could come from the recycling of (space) objects.

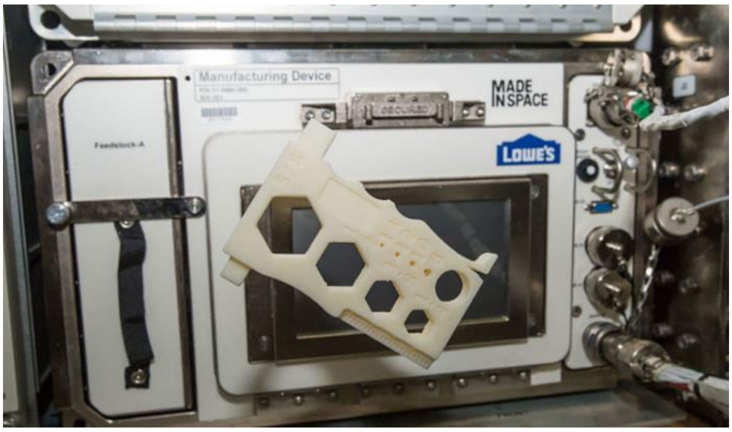

Figure 8 Made in Space 3D Printer on board of the ISS (Made in Space, a Redwire company)

Another example of space manufacturing is the US-company *Nanoracks*, which received a million-dollar contract from NASA[79] to investigate the conversion of spent upper stages into wet labs or experimental hubs.[80] Here, the large object size of the upper stages is the main reason for space manufacturing.

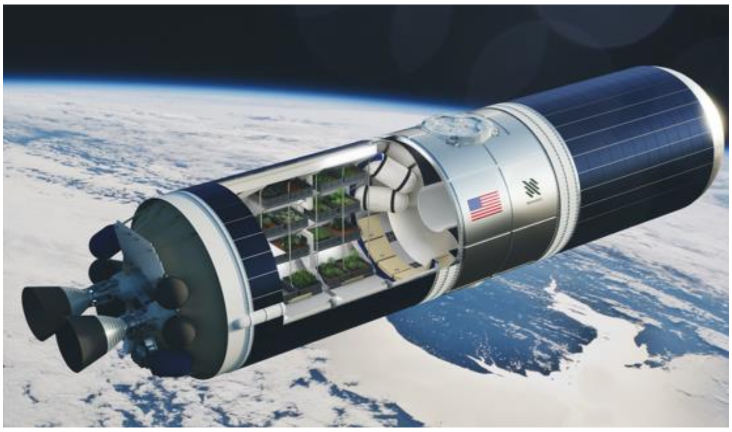

Figure 9: Outpost concept (Nanoracks (80))

Since recycled space material avoids expensive launch costs, it could (potentially) be offered at a lower price compared to Earth material. As in the previous scenarios, higher orbits would therefore provide a better *return of invest* (ROI). Second, space recycled material could offer structural advantages over Earth material:

- Much larger objects could be produced in space as no payload limitations needs to be considered.
- Thinner or more fragile objects can be produced in space, as the extreme physical launch conditions (occurring sound pressure, extreme accelerations) could be ignored, which could break these objects.[81]

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[78] 3D-Printing Materials - Wikipedia

[79] Nextstep-2 Contract for commercial habitat concept - Nanoracks

[80] Outpost - Nanoracks

[81] E.g., Ariane 6 Manual Chapter 3 - ArianeSpace

MISSION SCENARIO FOR RAW MATERIAL RECYCLING IN SPACE

A typical mission scenario for raw material recycling in space would consist out of the following steps:

- Identify the ideal space debris items.
  - The items would be easily accessible and would have a favourable ratio of raw materials and total weight. Ideally, several equivalent items exist to achieve scaling advantages.
- Approach the debris item in space
  - A dedicated recycling spaceship must be constructed. Ideally, this spacecraft can be derived from existing designs and reuse many components, such as propulsion technology, power supply, *Guidance Navigation & Control* (GNC), etc.
- Connect / dock with the space debris item.
  - The connection could occur on an existing docking plate or similar location. As already discussed, the future standardization of service interfaces would be beneficial.
- Tug the item to the recycling spot.
  - For the recycling process, a special location in space should be identified. As on Earth, it is ideally positioned near the place where the recycled material is used to avoid additional transport efforts.
- Dismantle the item to gain access to the raw materials.
  - If no other components continue to be used, mechanically crushing the entire object may be the easiest way.[82] Since some contamination of the recycled raw material is normally permitted, no further material sorting may be required (depending on the initial ratio of recycled material and total object weight).
- Process the raw material.
  - As a rule, raw material in space means metal, especially aluminium. Due to the low melting point of aluminium, melting would require between 500-600Wh per kg. This could be achieved by solar energy, either by electric melting furnaces[83] or via concentrated sunlight.[84]
- Generating new objects from the raw material
  - Although casting in low or microgravity is not easy, experiments have been successfully carried out on the ISS. Depending on the application, large or fragile objects can be cast or 3D-printed that cannot be launched from Earth into space due to payload volume limitations or the harsh conditions of a typical rocket launch.

CRITERIA FOR RAW MATERIAL RECYCLING IN SPACE

Recycling raw materials from space debris is not a silver bullet for everything. It is important to consider the given technological limitations as well as the financial aspects of a recycling mission. The main criteria can be summarized as follows.

- As described, recycling in space is more complex than on Earth. Therefore, if there is no terrestrial recycling process for a particular material, the chances of successful space-based recycling should be considered zero. This applies to smaller pieces of debris such as small explosion fragments, solid rocket motor slag or NaK droplets from nuclear reactors.

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[82] Industrial Shredder Types - Wikipedia

[83] Electrostatic Levitation Furnace - ISS National Lab

[84] SOLAM: Using solar energy to melt aluminium - DLR

- Complexity of the recycling process. Materials that are easier to recycle, such as aluminium due to its low melting point of 660°C, should have higher priority than materials with more complex recycling processes, such as titanium with a melting point of 1668°C, metal alloys with specific component ratios or composite materials.
- The amount of raw material recovered from the debris item must be estimated in advance. As more raw materials from the selected item could be recycled, as better the ROI of the recycling mission. A good understanding of the object composition is required. As mentioned earlier, a public record of such information would be beneficial.
- Before a recycling process can begin, the debris items must be caught or collected. Due to the high relative velocities, this is not trivial and requires a good understanding of the object itself, its exact trajectory, and movements (rotation, tumbling, etc.).
    - Support for Earth observation would be possible for larger objects such as satellites or rocket upper stages, depending on the orbital altitude.[85]
    - Small objects without reflective surfaces can only be viewed closer from space, if at all.[86]
- Objects with higher tumbling rates would need to be detumbled first. Different technology concept exists, which ranges from eddy current induction[87] via net and elastic tether[88], to remote LASER ablation[89] or thruster plume impingement[90] against the target.
- A secure connection to the debris must be established to allow the removal of the object and its transport to the recycling site.
    - For larger items, there are some technology concepts ranging from nets via robotic gripping tools (manipulators), harpoons to smaller thruster modules that would connect directly to the debris such as a tugboat.[91]
    - For smaller debris items, a secure connection is too complex due to the high relative velocities: the item could either strike through the trapping device (too soft) or reflected (too stiff) or could smash out additional debris items (too fragile). Finding the right balance for the wide variety of debris items remains a challenge.
- It is necessary to identify a location for the recycling site that minimizes the transport efforts between the original location of the debris, the recycling site and the final “place of use” (place, where the newly created object from the recycled raw material is used). Without customer demand, recycling raw materials in space would not be financially attractive.

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[85] Daylight space debris LASER ranging
[86] Space-Based Optical Observations of Space Debris
[87] Eddy currents applied to de-tumbling of space debris
[88] Detumbling of Space Debris by a Net and Elastic Tether
[89] Detumbling large space debris via LASER ablation
[90] Detumbling Space Debris via Thruster Plume Impingement
[91] Technologies for Space Debris Remediation - ESA

THE CASE FOR ALUMINIUM RECYCLING

There is hardly a resource readily available in space. But since the launch of Sputnik half a century ago, aluminium has been the material of choice for space structures of all types. Selected for its light weight and its ability to withstand the stresses that occur during launch and operation in space, aluminium was used on *Apollo* spacecrafts, the ISS as well as for the primary structures of NASA's *Orion MPCV* (Multi-Purpose Crew Vehicle) spacecraft.[92] Aluminium alloys consistently outperform other metals in areas such as mechanical stability, dampening, thermal management, and reduced weight. This also means that a large part of all space debris is made of aluminium. For example, the Ariane 5 ESC-A upper stage has a dry weight of around 3.7 tonnes with 2.4 tonnes of aluminium.[93] More than 60 of them will orbit Earth for the next decades or even centuries.[94]

Fortunately, terrestrial aluminium recycling is well known and established. For Europe, already up to 35 percent of the aluminium used comes from recycled aluminium, as Europe itself has hardly any natural aluminium sources. The *Circular Aluminium Action Plan* of the European Aluminium industry summarizes the most important aspects with the key factors listed here: [95]

- Aluminium is a circular material that can be recycled several times without losing its original properties.
- Aluminium recycling rates in Europe are among the highest in the automotive and building sectors, at over 90%.
- The aluminium recycling process requires only 5% of the energy needed to produce the primary metal, resulting in important energy and CO2 savings.

All these aspects are also relevant for space.

THE MOON AS THE IDEAL SPOT FOR SPACE MANUFACTURING

Beside a dedicated recycling site in higher orbits such as GEO, the Moon should be an ideal recycling site. The Moon offers (small) gravity forces that makes processing of raw materials easier than under "zero" gravity as in the LEO or GEO region. Machines, objects, and materials could be placed on its surface and securely fixed to apply the necessary forces during the recycling process.

Secondly, the great distance between the Moon and the Earth makes transport of (raw) materials very costly. Due to physics, the required transport energy is not distributed linearly. ¾ of the energy is already spent to reach LEO. From there, only 25% is needed to reach the Moon. A heavy weight transport from LEO to the Moon is therefore significantly cheaper than from Earth directly.

Thirdly, there are customers for raw materials on the Moon. The upcoming *International Lunar Research Station* (ILRS)[96] or the planned *Lunar Ground Station* described the in the *Global Exploration Roadmap* (GER)[97] will require a significant amount of space manufacturing and could therefore benefit from recycled raw materials. The earlier cited NASA study on the life supply of a LEO space station comes to comparable results

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[92] Aluminium in Aerospace - aluminum.org

[93] Bernd Leitenberger: "Europäische Trägerraketen 2", ISBN 978-3738642964

[94] Estimations of Lifetime for Launchers Debris in GTO

[95] Circular Economy - European Aluminium

[96] Russia & China Agreement on International Lunar Research Station - Space News

[97] Global Exploration Roadmap Supplement – Lunar Surface Exploration Scenario Update

for a lunar station:[98] *"The mission most favourable to recycling would be a long-term lunar base, since the resupply mass would be large, … and the launch cost would be much higher than for LEO due to the need for lunar transit and descent propulsion systems."* Although NASA is looking at a slightly different aspect, the launch cost factor for the construction material is comparable.

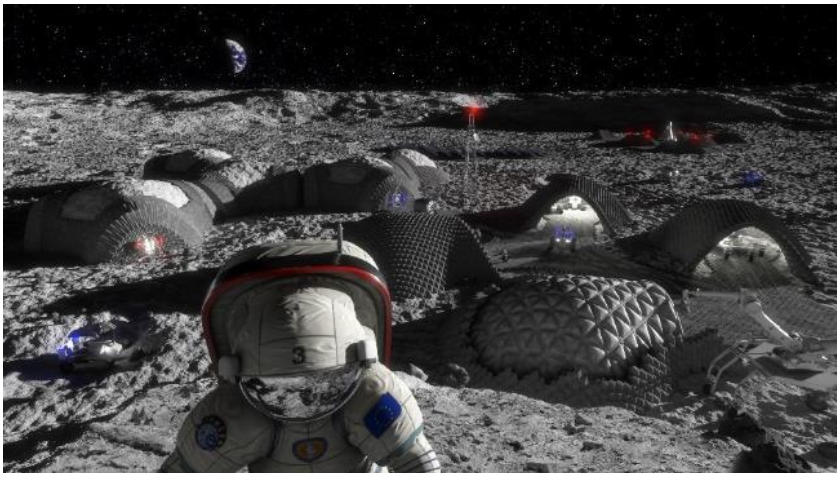

Figure 10 Concept of Moon station (ESA, Liquifer)

Currently, the material need for such a lunar station can only be estimated, since there is no final concept for a station yet. A good starting point is the ISS with about 400 tonnes of metal constructions without interior fittings.[99] NASA alone has spent 37 shuttle flights, or more than 100 billion US dollars on its assembly.[100] In the long term, however, the lunar station should be larger than the ISS, as the Moon is interesting in many respects: The mining of mineral resources on the Moon and the construction of observatories are already being intensively discussed and planned.[101] Realistically, over time, over 500 tonnes of metal could be needed on the Moon. At present, no European rocket would be able to transport such a quantity of material from Earth to the Moon, while the concept of space debris recycling described would be feasible for Europe.

A competitive source of construction materials on the Moon would be *In-Situ-Resource-Utilization* (ISRU).[102] Various methods and techniques are discussed to extract oxygen and metals from regolith.[103] However, their respective occurrences in the regolith vary depending on the location, mineralogy and even grain size. Although ISRU technologies may be promising in the future, they are still at an early stage, in which many years and decades are still needed for development.

Secondly, recycled material has an energy advantage over primary materials. While it requires a lot of energy and complex processes to extract primary aluminium out of its ore *bauxite*, due to its low melting point of around 660°C, it only needs 5% of the energy to melt and recycle the corresponding amount of secondary aluminium. This would also apply to space, in this case to the Moon. To obtain primary aluminium from regolith,

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[98] Much Lower Launch Costs Make Resupply Cheaper than Recycling for Space Life Support - NASA
[99] Building the International Space Station - ESA
[100] Assembly of the International Space Station - Wikipedia
[101] Moon 2 Mars - NASA
[102] ISRU - NASA
[103] ESA opens oxygen plant making air out of Moondust - ESA

a similar amount of energy would be required as on Earth.[104] Alternatively, secondary aluminium in space could be recycled as often as it is needed with much less energy consumption, as on Earth.

Together with its research partners, Orbit Recycling has developed an early recycling processes and cast the first aluminium objects from space debris in regolith simulant.[105] Today, large, and simple objects such as wall segments can be poured. Over time, with improved process technologies, more precise objects like doors, airlocks and other objects could be manufactured. A joint research project of ESA (*European Astronaut Centre* EAC), TU Berlin and Orbit Recycling will investigate this recycling process evolution in the coming years. The chapter "*Aluminium Casting in Regolith*" in Part 2 describes this activity in more details.

Figure 11 Regolith mould and resulting aluminium cast ("rover shelter", Baasch, Smith, Orbit Recycling)

In the US, the idea of space manufacturing is driven by DARPA through the *Novel Orbital and Moon Manufacturing, Materials and Mass-efficient Design* (NOM4D) program.[106] With NOM4D, DARPA will work with participants in three 18-month phases to develop precise, mass efficient structures that could be used for on-orbit construction. Although it focuses on the three applications of large solar arrays, large radio frequency reflector antennas, and segmented infrared reflective optics, manufacturing on the Moon also plays a key role.

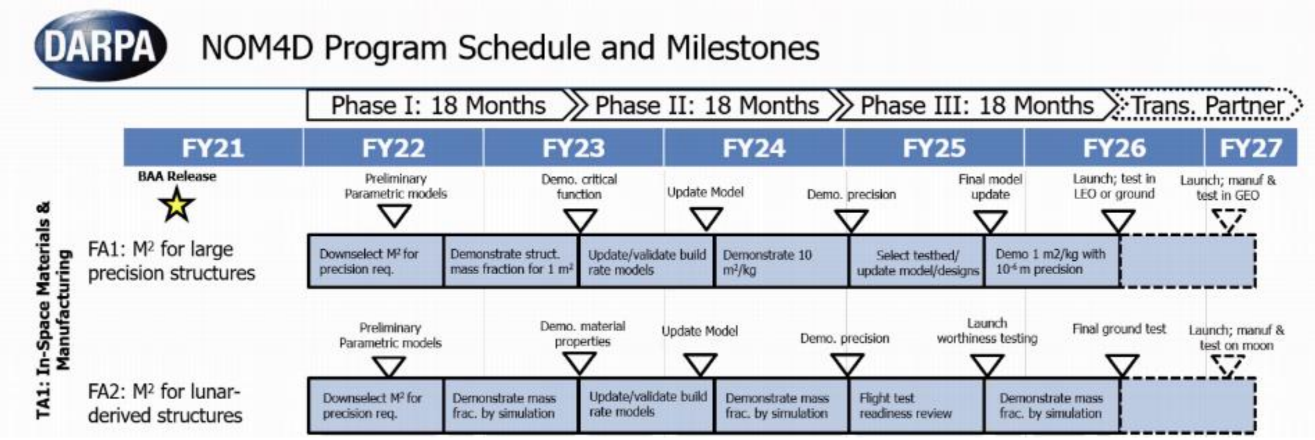

Figure 12 Current NOM4D Timeline (DARPA)

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[104] Alternative processes are currently studied, but haven`t reached the required maturity level so far.

[105] Regolith as mold material for aluminium casting on the Moon - Orbit Recycling et.al.

[106] DARPA NOM4D Proposers Day

RECOMMENDED NEXT STEPS

Of all the recycling options, raw material recycling offers the greatest potential: It has the highest maturity and at the same time the least demanding process technology. In addition, the largest mass amount of all space debris is addressed. Since the recycled material is newly produced, no space aging affects must be considered, which offers very flexible use cases for the raw materials.

As the recycling of space debris is within Europe`s technological capabilities, ESA should consider using recycled material for future space manufacturing activities, especially on the Moon. Even if the material did not initially come from orbital space debris, lunar landers or rover material could be recycled after their missions to avoid or at least reduce additional material transports from Earth. These end-of-life recycling aspects should be included in future mission profiles at ESA.

Over time, the end-of life / recycling criteria should also be included for satellite missions to contribute to the creation of a space-based recycling industry. Typical targets should be future generations of the *Galileo* fleet or planetary missions to Moon, Mars, and other destinations. At these remote locations, any recyclable (raw) material would be a valuable, easily accessible space resource for subsequent missions.

Finally, space debris should be officially considered as another (important) space resource to be explored at the *European Space Resources Innovation Centre* (ESRIC).[107]

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[107] Research at ESRIC, Luxembourg

LEGAL ASPECTS OF SPACE DEBRIS (SIMPLIFIED OVERVIEW)

A brief overview of this topic is available for completeness, quoted from the article "Current Trends and Challenges in International Space Law" by Dr Dionysia-Theodora Avgerinopoulou and Katerina Stolis, European Institute of Law, Science and Technology.

CHAPTER SUMMARY

The following thesis about legal situation regarding space debris is postulated and substantiated:

T-LA-1	Neither the UN space treaties nor the most recent Space Law provisions address the space debris problem.

By comparing the space situation with Earth, the following conclusion is derived from the thesis:

C-LA-1	A legislation like the law of salvage under maritime law could be a solution to allow active debris removal from another country.	T-LA-1

From the article *"Current Trends and Challenges in International Space Law"*: [108]

"… Under the 1972 Liability Convention the "launching state is liable for damage caused to a space object or to persons or property on board of another state" if the damage is due to negligence. This assumption raises two important issues: on the one hand, the difficultly to prove the negligence, since "space traffic rules" do not systematic exist[109] and on the other hand, the insurmountable problem to determine in most cases who is responsible considering the uncertainty of origin of most space debris.

The absence of a legally binding definition of space debris is another issue that arises, even though it is widely accepted that the term comprises everything from small parts to "dead" satellites.[110] The Registration Convention also has relevance, since the availability of information can be essential in the case of a collision between space objects providing identification. However, this Convention entails problems of terminology that leave enough space for interpretation considering the term "space object". …

The UNCOPUOS Space Debris Mitigation Guidelines do not provide a holistic solution to the issue, even though they constitute a remarkable step towards minimizing risks related to space debris. They could, however, "create a basis for legally binding rules to be negotiated at some time in the future."[111] The process to establish binding rules for this issue is a slow one, due to two major factors according to Schrogl: first, "space powers did

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[108] Article Current Trends and Challenges in Space Law, European Space Sciences Committee

[109] Viikari, L., 2015. Environmental aspects of space activities. In: F. von der Dunk & F. Tronchetti, eds. Handbook of space law. Cheltenham and Northampton: Edward Elgar Publishing: Research Handbooks in International Law, pp. 717-769.

[110] The term in use at deliberations in UNCOPUOS refers to all man-made objects, including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional. For more information, see Tortora, J.J (2011). Studies in Space Policy. London and New York: Springer.

[111] See Review of the Legal Aspects of the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space, with a View to Transforming the Guidelines into a Set of Principles to be adopted by the General Assembly, Working Paper Submitted by the Czech Republic, 50th session of the LSC, 2011, UN Doc. A/AC.105/C.2/L.283, para. 18

not want to develop rules jointly with states not involved in space activities" and secondly "*they are reluctant to bind themselves to technical modifications that are necessary to harmonize with the guidelines*".[112]

… One of the possible solutions to the space debris issue is the establishment of a piece of legislation similar to the law of salvage under maritime law, which will eliminate any possibility of removing another country's debris without permission to be considered illegal, since the UN space treaties recognize no termination of the jurisdiction and control over a space object.[113] *A major improvement could be the review of the Registration Convention so that notifications concerning explosions and break-ups of registered space objects would become compulsory. Part of the solution of this issue could also be the on-orbit satellite servicing (OOS). The most vital solution for the space debris issue is the clear universal distinction between functional spacecraft and non-functional space debris and the adoption of legally binding definitions for all ambiguous terms. …*

Overall, the preferred solution to resolve all legal questions and to provide a holistic approach to this issue could be through the adoption of an international treaty[114] *that will include binding legal and technical measures regulating the prevention and management of space debris at all stages of a space operation. …"*

RECOMMENDED NEXT STEPS

Compared to Earth, the ownership or authority of a space object, functional or debris, does not terminate. Therefore, the recycling of space debris would not be possible without the explicit agreement of the registered owner of such an object. Since this would also be the case for any space servicing operation, like refuelling, re-orbiting etc., a legal basis for these activities must be developed. Ideally, a piece of legislation like the law of salvage under maritime law will be adopted internationally.

ESA should continue its support and funding of the *European Centre for Space Law* (ECSL) and should encourage ECSL to continue to focus on the topic of space debris remediation and the recycling of space debris to provide a solid legal basis for future activities from Europe in this area.

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[112] Schrogl, K.-U., 2011. Space and its sustainable uses. In: C. Brunner & A. Soucek, eds. Outer Space in Society, Politics and Law. Wien and New York: Springer in Space Policy Volume 8, pp. 604-618.

[113] Schwetje, K., 1990. Liability and Space Debris. In: K. Böckstiegel, ed. Environmental Aspects of Activities in Outer Space: State of the Law and Measures of Protection. Cologne: C. Heymanns Verlag, pp. 36-40.

[114] Kopal, V., 2008. An Introduction to Space Law. 3rd revised edition ed. Netherlands: Kluwer Law International, p. 103.

PART 2

Technical Implementation Concepts

RECYCLING CONCEPT OVERVIEW

As discussed in Part 1, not all types of space debris are suitable for recycling. A rule of thumb would be that if a process for a particular material or object type does not exist on Earth, recycling does not work in space either. “Existing” in this case is meant in a broader way and implies a completely or at least mainly automated recycling process. Raw material recycling is the most attractive recycling option for space debris due to its low technical requirements and flexible usage scenarios.

The second part of this study describes the specific application of aluminium recycling from space debris for lunar constructions. This case was identified in Part 1 as the most attractive scenario, both from a financial and a technical point of view. The main technical aspects of this use case are discussed as follows:

- Selection of the most suitable space debris objects for recycling. Selection criteria are based on
    - Weight, composition, accessibility (e.g., orbit, potential tumbling rates) and the number of equivalent items to achieve scaling advantages.
    - Results of preliminary ground observation of selected space debris items to validate their orbits and tumbling rates. The observations were provided by Orbit Recycling`s partner, CastelGAUSS Observatory, Italy and Fraunhofer FHR TIRA, Germany
    - General risk reduction by removing the debris
    - A precursor mission idea is described to validate the identified tumbling rates with a small satellite and to visually inspect the selected debris item.
- A brief overview of possible detumbling technologies for space debris items is given.
    - If required, the identified tumbling rate of the debris item could be reduced in advance to allow a secure connection between the recycling space tug and the debris item.
- A brief overview of existing gripping technology is summarized.
- Various concepts for a recycling space tug mission are presented, including
    - A Vega-C launchable design, starting in LEO.
    - An Ariane 64 launchable design, starting in GTO.
- A simplified analysis of the proposed Moon landing and impact scenario is described.
- The results of a lunar surface debris recovery mission concept are presented.
- An overview of aluminium smelting and casting in regolith processes is given, including the concept of concentrated sunlight sintering and melting via Fresnel lenses by Frank Koch – Orbit Recycling.

SELECTING THE IDEAL SPACE DEBRIS ITEMS FOR RECYCLING

CHAPTER SUMMARY

This chapter deals with various criteria for selecting the most suitable objects for raw material recycling, in particular aluminium recycling. Part 1 has derived this solution as the most attractive recycling concept for space debris in general. The criteria include the material composition of the space debris object, the "accessibility" of the object, as well as the associated risks of the objects for other space activities or the Earth since these risks are eliminated by the removal of the object from orbit.

As a result of the criteria evaluation, the most suitable space debris for raw material recycling are derelict upper stages in GTO. Europe could recover around 150 tonnes of aluminium from over 60 objects, ideally suited for constructions on the Moon and could remove a large part of its entire space debris mass.

Based on observations made, only a few upper stages could be approached immediately, while others need to be detumbled first, either naturally over time or externally. A precursor mission is presented to approach a derelict upper stage, to visually examine the material state and to validate its tumbling behaviour.

SELECTION CRITERION 1: MATERIAL COMPOSITION

In the previous chapter "*Criteria for Raw Material Recycling in Space*", a checklist of successful raw material recycling activities on Earth was developed to determine the most suitable space debris objects for recycling. The checklist contained the following criteria for the ideal material composition:

- Advance knowledge about the composition of the debris is available (e.g., a construction plan is still available).
- There must be a terrestrial recycling process for the object or the material (e.g., for aluminium).
- The terrestrial process must not be complex or manual (e.g., no manual dismantling, low melting point)
- An optimal ratio of recycled material and total weight of the debris is indicated (e.g., higher than 20%).
- The total amount of recycled material per debris object is "high enough" (e.g., higher than 20kg).
- The object must be traceable (e.g., large enough to be "visible" from Earth or space).
- If necessary, the debris must be detumbled; therefore, the object or its material must react to external forces (e.g., by eddy current induction).
- The object is "connectable"; ideally, a connection interface exists (e.g., nozzle, payload adapter, …).
- There should be multiple identical objects to allow scaling effects on multiple recycling missions.
- A use case (and location) can be identified for the recycled material (e.g., reuse of aluminium for construction of the upcoming lunar ground station).

In recent years, Orbit Recycling has analysed publicly available space debris catalogues such as DISCOS and other data sources to identify the debris objects that are best suited for recycling. The results were shared with experts at European space events and conferences such as *Space Explorations Masters*, *INNOSpace Masters* and others to gather external feedback on the proposed use cases and recycling concepts. This includes several interviews with ESA experts as part of this study. The conclusions reached in this course were as follows:

- Since there is no recycling process or use case for NaK-droplets or solid motor slags, these items have been excluded from the recycling target list.
- All objects smaller than 10cm were excluded, as the high relative velocity would prevent any safe collection of these items without risking the emergence of new debris fragments due to uncontrolled collisions.[115] In addition, a size of 10cm seems to be the minimum for safe trajectory tracking of the object with affordable efforts, either from Earth or from space.[116]
- All items lighter than 150kg dry weight have been excluded, as the amount of recyclable structural components usually does not exceed 15-20% of the total weight, which would result in less than 30kg of recyclable material per object. This small amount would not justify the cost of a recycling mission.
- All unique, large (scientific) satellites, e.g., for Earth or space observation purposes, have been excluded because the technology required to approach, collect, and recycle them would be unique to each object and a space recycling mission would not benefit from any scaling effects in the future.
- For legal reasons, and to reflect the role of ESA in this study, objects that were not launched from Europe or with a European launcher and are not owned or operated by a European legal entity have been excluded at this stage.

In the end, the following concise list of potential space debris targets suitable for raw material recycling remained, summarized in the table below:

Criteria / Target	Satellite (mega) constellation (LEO)	"Galileo" satellite fleet (MEO)	Large GEO satellites	Ariane 5 ESC-A upper stages
Object Composition	Known, not public.	Known, not public.	Known, not public.	Known, not public.
Identified Recycling Material (RM)	Metal / Aluminium	Metal / Aluminium	Metal / Aluminium	Metal / Aluminium
RM ratio vs. total (dry) weight	<15%	<20%	<25%	>60%
RM amount per object	<50kg	<140kg	<250kg	>2,000kg
Object orbit	LEO	MEO	GEO	(Mainly) GTO
Object traceable from	Earth & space	Earth & space	Earth & space	Earth & space
Object interfaces for connecting	Proprietary	Payload Adapter	Payload Adapter Nozzle	Nozzle Payload Adapter
Scaling benefits (no. of objects)	Hundreds to Thousands	Dozens (~26)	Dozens (~20-50 per bus)	Dozens (~60 ESC-A,)

Table 1: Evaluation of Space Debris Criteria

Although this analysis has been carried out over a period of several man-years with best efforts, it is still limited. For the above list, the object composition is considered as "*Known, not public*", since the manufacturers of the objects still exist, the objects were created recently and the blueprints therefore also exist, although they are

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[115] Hypervelocity Impacts and Protecting Spacecraft - ESA

[116] Scanning and Observing - ESA

not usually published for public access. Nevertheless, some information is available to allow "*best guesses*" for the above estimates.[117]

Since component recycling from old space objects is still a manual process and therefore too complex and costly, today only raw material recycling remains as a serious option for space debris. This can change over time if there is standardization of component interfaces and if more objects implement such standardized components. As mentioned in Part 1, ESA could play a crucial role in advancing this international standardization programme with its own satellite procurement programme for Earth observation satellites and responsibility for the technical guidelines and interfaces of the *Galileo* program.

From all raw materials used in space objects, aluminium is the least complex material for recycling. The recycling process on Earth is quite simple, the material has a low melting point of around 660°C and aluminium could be used in many ways in space, especially for structural components such as wall elements, support systems, conductors or power lines, cooling blades (fins), tools and even as propulsion material.

Looking at the overall results, old upper stages are the best compromise for recycling space debris. They have the largest amount of recycling material per object of more than 2 tons, the highest ratio of recycling material to object dry weight of around 60%, they are large enough to be easily traced from Earth as well as from space and were mostly left in a highly elliptical orbit (*GEO Transfer Orbit* - GTO). Since more of 60 of them are still available in space just from the European Ariane 5 ESC-A type, any specific development or mission activity would directly benefit from a large scaling effect.[118]

Figure 13 Ariane 5 ESC-A Upper Stage (ESA, Arianespace)

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[117] A better analysis of the existing space debris would be possible, if the existing data sets were extended to include the material compositions of the debris, as proposed in Part 1 of this study. This would reduce the current uncertainties regarding the estimated amount of recycled material per object.

[118] In addition, more than 80 additional but lighter upper stages of previous Ariane launchers are drifting in space, which have comparable (oxygen) tanks with the same aluminium alloys. They offer similar connection points with identical nozzle and payload adapters, further increasing the scaling advantages.

SELECTION CRITERION 2: ACCESSIBILITY

In addition to the material composition, the "*accessibility*" of the material is another important criterion for the selection of the most suitable space debris objects for recycling. In this case, accessibility means how easily the debris object could be approached and whether a connection with the object could be established without too much effort.

GENERAL DETECTABILITY OF THE SPACE DEBRIS OBJECT

To approach an object in space, its trajectory must be known and traceable. Objects larger than 10cm can be tracked from Earth in LEO without any problems, either via classical optical observatories[119], LASER[120] or RADAR systems[121]. Higher orbits such as GTO or GEO require more sensitive instruments or different technologies (frequencies).

All identified object classes from Table 1 are traceable from Earth. The objects are regularly tracked, and the trajectories are known. The approach to these objects in space up to a certain distance is therefore considered technically possible. (Visual) Inspection missions at satellites such as *Hubble*, ISS supply missions or the ESA concept of *e.Inspector*[122] for the satellite *Envisat* justify this assumption.

As part of the JAXA CRD2 program,[123] JAXA and Astroscale are developing technology to approach a Japanese H2A rocket upper stage with dimensions comparable to the Ariane 5 ESC-A type. The upcoming *CleanSpace-1* mission is developing technology to approach a non-metallic, black space debris object,[124] that is even more difficult to achieve than an approach of the above object classes. Nevertheless, larger objects such as the recommended upper stages or GEO satellites would always be easier to discover and detectable from a large distance with the (limited) instruments of a recycling space tug than the small satellites of a mega constellations in LEO or the *Galileo* fleet in MEO.

In the future, "*more-easily-detectable-objects-in-space"* could be achieved by implementing specific tools, e.g., passive RADAR or LASER retro-reflectors[125] attached to satellites or upper stages, even equipped with a unique identifier. They are designed to reflect the light back in the same direction from which it originates, to allow independent measurements of the satellite's position. In addition, markers on the target can be used to support relative navigation between the object and a recycling space tug. Similar technology was used for the *Automated Transfer Vehicle* (ATV) fleet to achieve automated rendezvous and docking with the ISS.[126]

ESA, which itself operates a large fleet of satellite, should consider requiring such passive reflectors and markers for future generations of its own satellites to begin the widespread use of such tools. Future space servicing or recycling missions would benefit directly from such reflectors. Ideally, the reflectors and the

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[119] CastelGAUSS Observatory, Italy
[120] Observatory Zimmerwald, University of Bern
[121] Space Observation RADAR TIRA - Fraunhofer FHR
[122] e.Inspector at Clean Space Industrial Days 2017 - ESA
[123] Commercial Removal of Debris Demonstration (CRD2) - JAXA
[124] ClearSpace-1 captures Vespa - ESA
[125] LASER Retroreflectors (Catch it if you can) - ESA
[126] ISS Services: ATV-5

markers will be combined in the future to support both scenarios. A concept of combining passive retroreflector and marker is shown in the appendix in "*Retroreflectors and Markers*". Orbit Recycling proposes a dedicated ESA research and development programme to foster this development.

TUMBLING RATES OF SPACE DEBRIS OBJECTS

To gain access to the recycling material, a secure connection must first be established with the debris item. To do this, each recycling space tug would have to synchronize its own movements with the target object before such a connection can be established. This harmonization shall include the trajectories and the (corresponding) velocities in space. In addition, each rotation of the objects must be synchronized. This overall concept is successfully used in the already mentioned life-cycle extension missions between large GEO satellites and the *Mission Extension Vehicle MEV-1* and *MEV-2.*[127]

In general, the rotational behaviour of a satellite is controlled by the satellite itself and / or the corresponding operation centre. Therefore, if the satellite is still functional, the rotation period should be considered known, low and "*possible for synchronization*".[128] However, since most old space debris objects must be considered "*uncooperative*" targets, complex, costly manoeuvres that are hardly proven in space would be required to synchronize the recycling space tug with the target. These manoeuvres can take a while and require a lot of (costly) fuel, which increases the recycling space tug weight and thus its launch costs. Objects that are best suited for recycling would therefore be slowly tumbling objects or objects that could be detumbled in an affordable way before the required synchronization between the recycling space tug and the target would be started.

The tumbling rates of space objects can be estimated from object observations to some accuracy. Light curve measurements[129] are often used, but RADAR and LASER observations are also possible. These established methods have been used worldwide for decades, and dozens of published articles cover observational results of different object classes and orbit heights.

TUMBLING RATES OF LEO SATELLITES AND OTHER LEO SPACE DEBRIS OBJECTS

In LEO, stabilizing effects from gravity and the Earth' magnetic field usually keep the rotation of metallic space debris objects at an acceptable speed.[130] Nevertheless, (non-metallic) space debris objects can develop different tumbling behaviour due to additional external effects and forces (e.g., atmospheric drag, sunlight radiation pressure, collisions with natural and artificial debris and others). At the 7th European Conference on Space Debris, a case study of the *Swisscube* satellite in LEO by Pittet, Silha, Schildknecht et. al. was presented.[131] To determine the rotation period of the target, various technologies were used, which are shown in the table below as an example of a small satellite (*Swisscube*) in LEO.

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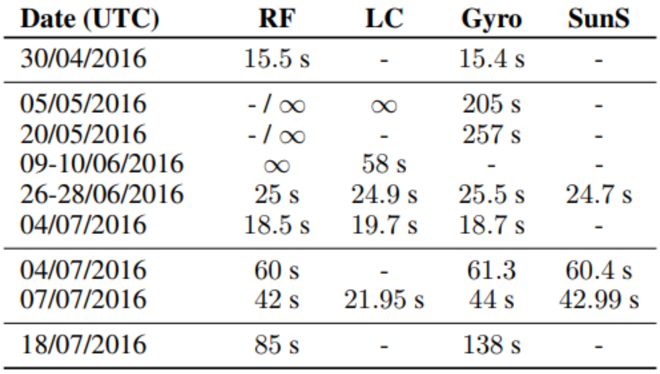
[127] MEV-1 & Target Synchronization (Video on YouTube)

[128] Some satellites are stabilized in spaces by high rotations around a specific object axis. As long as the satellite is operational, this rotation could be reduced for the connection approach of the recycling space tug.

[129] Optical Light Curve Observations to Determine Attitude States of Space Debris

[130] Attitude Dynamics of Debris Resulting from Upper Stage Fragmentation in Low Earth Orbit

[131] Space Debris Attitude Determination of Faint LEO Objects using Photometry



Date (UTC)	RF	LC	Gyro	SunS
30/04/2016	15.5 s	-	15.4 s	-
05/05/2016	- / ∞	∞	205 s	-
20/05/2016	- / ∞	-	257 s	-
09-10/06/2016	∞	58 s	-	-
26-28/06/2016	25 s	24.9 s	25.5 s	24.7 s
04/07/2016	18.5 s	19.7 s	18.7 s	-
04/07/2016	60 s	-	61.3	60.4 s
07/07/2016	42 s	21.95 s	44 s	42.99 s
18/07/2016	85 s	-	138 s	-

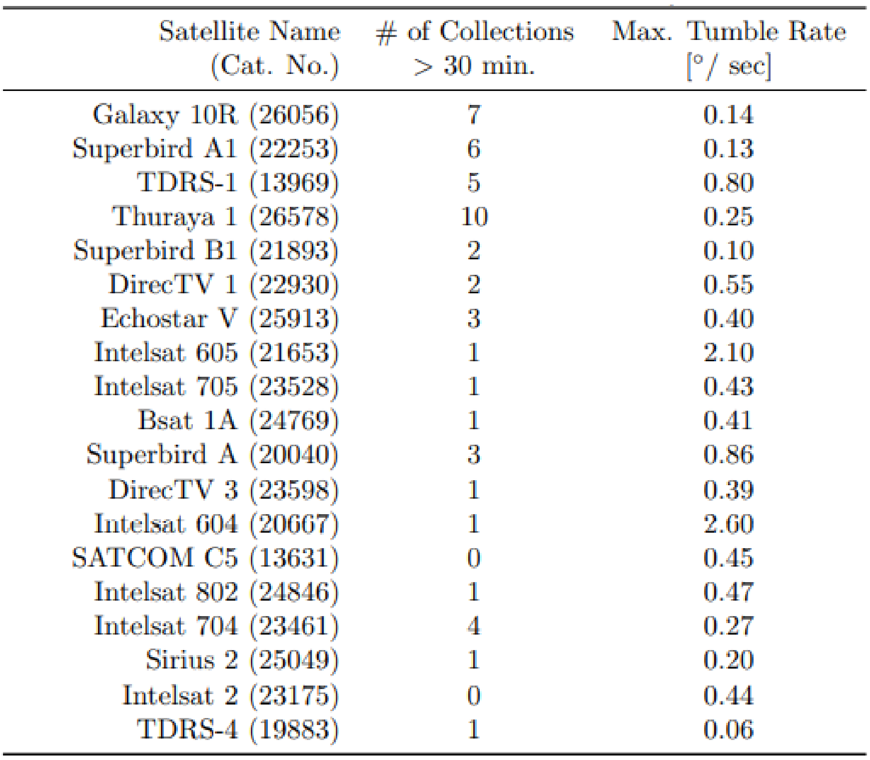
Table 2: Swisscube rotation frequency (Pittet et.al. (131))

Table 2: Comparison of the extracted period. "∞" signifies a period too long to be reliably observed. *RF* = radio signal analysis, *LC* f= light-curve, *Gyro* f= gyroscopes; *SunS* = the sun-sensor extracted value.

Since LEO objects have already been excluded from the most suitable target list by selection criterion 1, no further analysis of other tumbling rates was performed for this object category.

TUMBLING RATES OF GEO SATELLITES

In GEO, most of the satellites examined tumble below 1°/sec, as shown in Table 3.[132] As far as the tumbling rates are concerned, these satellites would be well suited for a potential recycling mission.



Satellite Name (Cat. No.)	# of Collections > 30 min.	Max. Tumble Rate [°/ sec]
Galaxy 10R (26056)	7	0.14
Superbird A1 (22253)	6	0.13
TDRS-1 (13969)	5	0.80
Thuraya 1 (26578)	10	0.25
Superbird B1 (21893)	2	0.10
DirecTV 1 (22930)	2	0.55
Echostar V (25913)	3	0.40
Intelsat 605 (21653)	1	2.10
Intelsat 705 (23528)	1	0.43
Bsat 1A (24769)	1	0.41
Superbird A (20040)	3	0.86
DirecTV 3 (23598)	1	0.39
Intelsat 604 (20667)	1	2.60
SATCOM C5 (13631)	0	0.45
Intelsat 802 (24846)	1	0.47
Intelsat 704 (23461)	4	0.27
Sirius 2 (25049)	1	0.20
Intelsat 2 (23175)	0	0.44
TDRS-4 (19883)	1	0.06

Table 3: Tumbling Rates of GEO Satellites (Cognion, Albuja, Scheeres (132))

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[132] Tumbling rates of inactive GEO satellites

TUMBLING RATES OF UPPER STAGES IN GTO

For derelict upper stages, only a few tumbling rates were observed in LEO in the past. Unfortunately, the results of LEO cannot be applied to the GTO environment: for GTO, different gravitational and space environmental effects must be considered, which seriously affects the rotation behaviour of the upper stages.[133]

Orbit Recycling has teamed up with Mr. Sergei Schmalz from the Castelgrande Observatory in Italy to carry out own observations of Ariane 5 ESC-A upper stages in GTO. The results are visualized in the following graphic. Overall, most of the Ariane 5 upper stages have a rotation time between 1 second and 10 seconds, which initially makes them less attractive for approaching than GEO satellites. Nevertheless, a few of the upper stages have an acceptable rotation period of up to 30 seconds and more.[134]

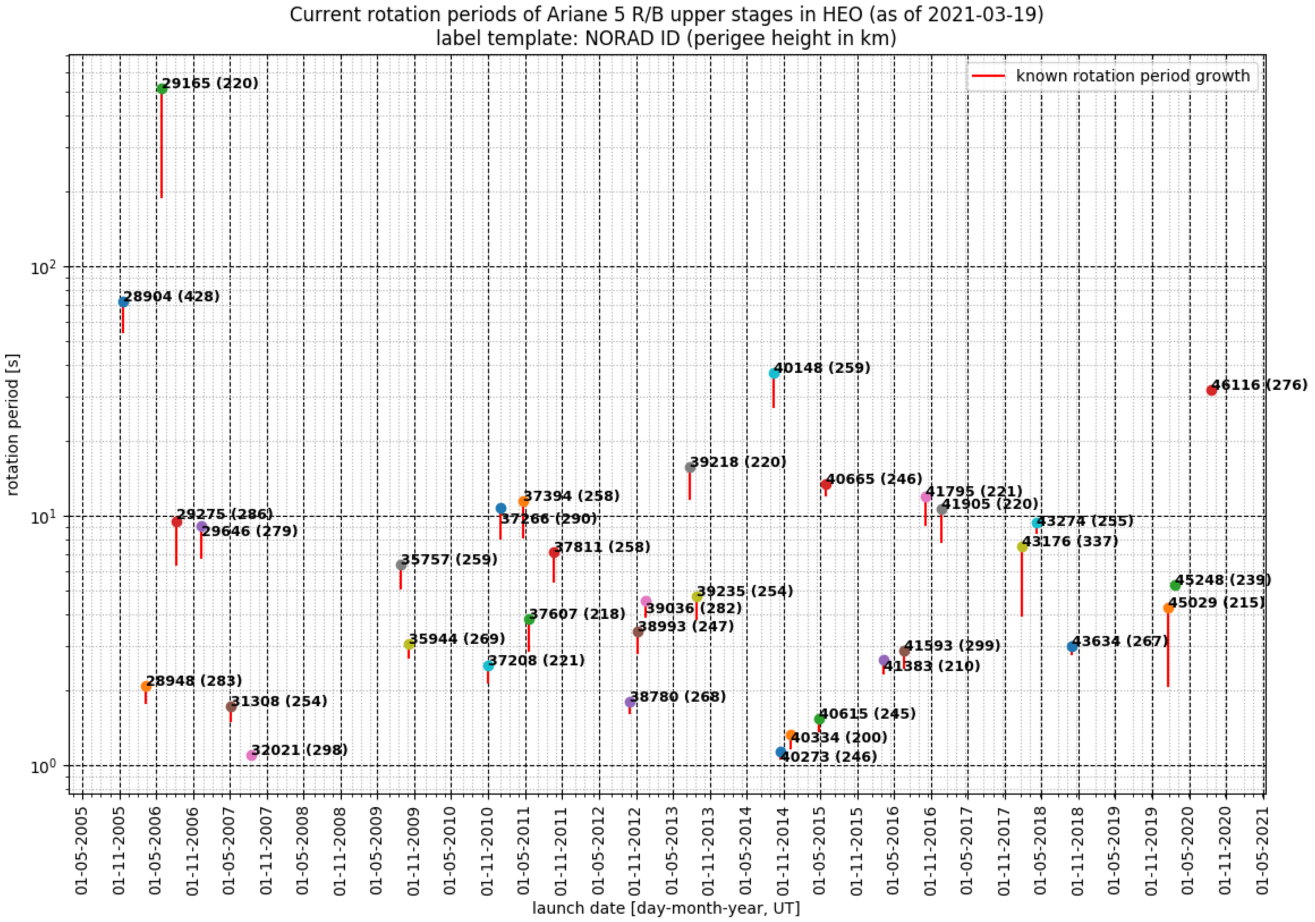

Figure 14: Rotation Periods of Ariane 5 ESC-A upper stages in GTO (Schmalz)

In addition, Mr. Schmalz not only observed most ESC-A objects but collected historical data from several observatories to find out if the rotation frequency of the upper stages would change over time. All upper stages are deaccelerating over time, as the NORAD ID 29275 shows exemplarily. Further examples can be found in the appendix at "*Examples of the Natural Growth of Upper Stage Rotation Period*".

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[133] Dynamical Lifetime Survey of Geostationary Transfer Orbits

[134] The latest collected data can be found in the appendix at "*Current Upper Stage Rotation Periods*".

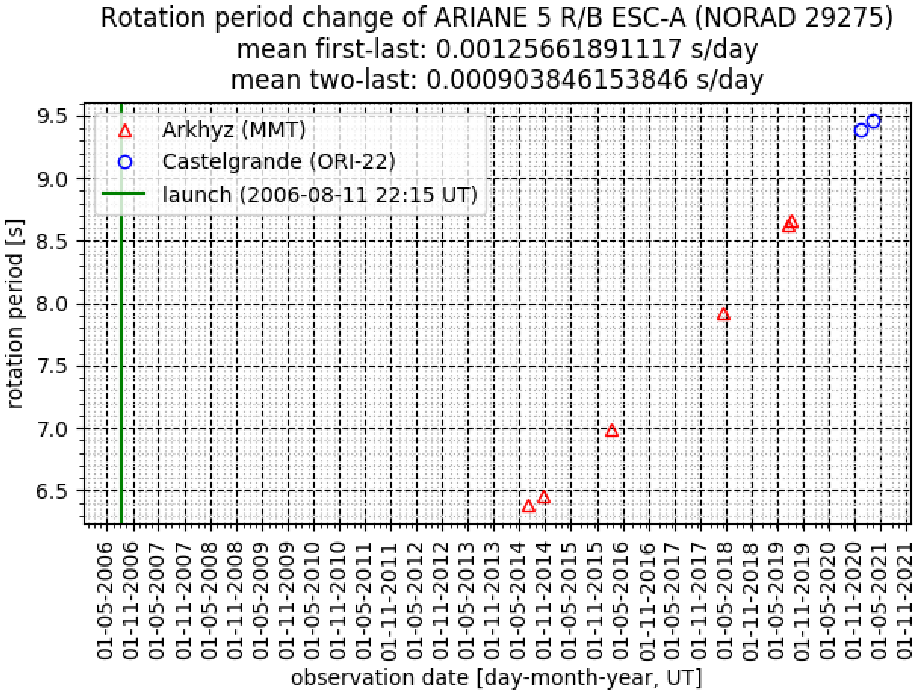

Figure 15: Rotation Period Change Over Time (Schmalz)

With the ever-increasing rotation periods, more upper stages would become candidates over time as a potential recycling target for space debris.

In addition to the light curve measurements by Mr. Schmalz from Castelgrande, the Fraunhofer FHR Institute[135] has supplemented the observations of the Ariane 5 ESC-A upper stages in GTO with its *Tracking and Imaging Radar* (TIRA) capabilities. Radar techniques come with a number of advantages that make them very competitive and sought-after. Owing to the frequency bands used by radar and its active nature as a sensor, radar observations can be performed at any time, under almost any weather conditions and are independent of target illumination conditions. Radar systems offer high *pulse repetition frequencies* (PRF) leading to high-cadence observational data and easily gain insights into fast rotating space objects. Furthermore, long observations are easily attainable with radar. TIRA can achieve observation length of tens of minutes at a time, exploring samples of very slow rotators too. Combining the above advantages, radar can offer highly detailed and statistically robust studies of promising objects; for instance, objects (pre-)selected from optical surveys as well as for cross-validation between optical and radar scientific results.

Fraunhofer FHR has already gained experiences with GTO upper stage monitoring and carried out its own tests in the past:

> *"If we assume however, that they are still intact, their most probable attitude might be a gravity gradient stabilized mode in combination with a precession or spinning. This may be supported by the fact, that these stages are in GTO since more than four years, so that they might have lost their initial rotational energy due to dissipation effects."*[136]

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[135] Space Observation Radar TIRA - Fraunhofer FHR

[136] Radar measurements and analyses of spent ARIANE rocket bodies in geostationary transfer orbits

In the context of the present study, a small sample of spent Ariane 5 upper stages in GTO was observed with TIRA with the aim of characterizing their rotational status. These constitute precursor observations and analysis aimed at meaningful sub-samples of interesting upper stage targets in GTO with the goal to prove the feasibility and scientific relevance of a larger scale study. The table below lists the observed Ariane 5 ESC-A upper stages with their NORAD ID and relevant parameters.

Object	NORAD ID	Intl. Designator	Date	Total Obs. Duration (sec.)	Min Range (km)	Max. Range (km)
Ariane 5 R/B	29498	2006-043E	2021.03.08	3718.8	6158	20283
Ariane 5 R/B	38780	2012-051C	2021.03.09	4450.2	6467	23775
Ariane 5 R/B	43176	2018-012C	2021.03.12	1174.8	5589	9495
Ariane 5 R/B	28904	2005-046C	2021.05.10	2228.4	9541	17427

Table 4: Observational Parameters for ESC-A in GTO (Fraunhofer FHR)

Relevant to this study is the radar cross section (RCS) and its temporal variation within the observation interval. The RCS plot shows the relative intensity of the backscattered radiation in decibels relative to one square meter (dBsm) as a function of time. As an example, Figure 16 shows the temporal evolution of the RCS of the upper stage with the NORAD ID 28904 during the observation on May 10, 2021. The rapid temporal variability of the RCS and the periodically repeating pattern therein indicate a relatively fast rotation of the object.

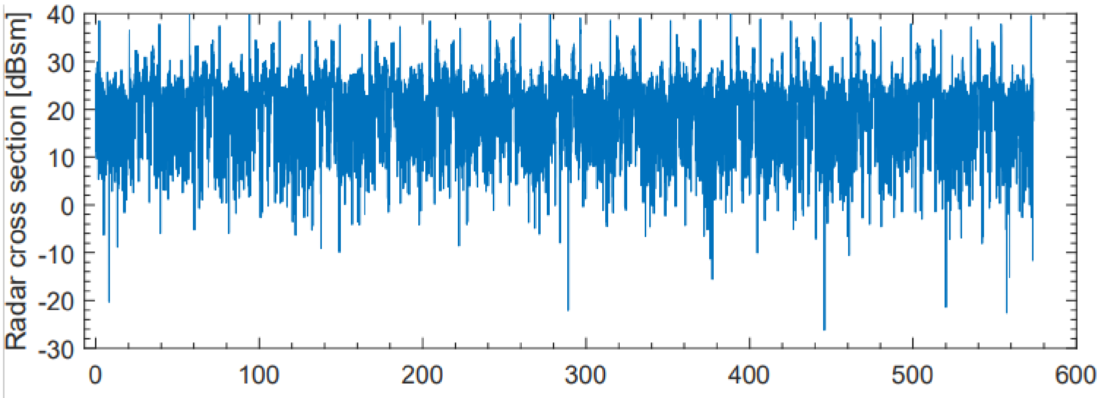

Figure 16: Time since observation start [sec.] (Fraunhofer FHR)

For the extraction of scientific results and characterization of the RCS signatures of the aforementioned targets a large suite of time series analysis and periodicity extraction methods were utilized. The subsequent periodicity analysis revealed that three out of the four observed targets, namely Ariane 5 R/B 29498, 38780, and 43176, show relatively fast periodicity in their RCS signatures. Periods of the order of seconds were the dominant components of their RCS signatures. Slower, but lower-power, periods characterizing parts of the respective observations are present. The situation appears different for the fourth object, namely Ariane 5 R/B 28904 shown above. A significant fast component, with a period of 4.6 s, as well as a significant slower period of 36.8 s were identified. The latter characterized the RCS signature in its entirety and may well be associated with the large-scale apparent rotational period of the object.

In general, the observation from Fraunhofer FHR matches the lightcurve observation from Mr. Schmalz, Castelgrande. The precursor study offered promising first results and the methods used can be extended to larger samples of objects in GTO with the goal of detailed characterization. The relevance of such an extension is apparent and will become a necessity given the need for high-quality data, crucial to the success of any future space servicing or space debris recycling mission in GTO.

The findings for each individual case based on the time series analysis as well as more background information about RCS and TIRA can be found in the appendix "*Investigation of Ariane 5 Upper Stages in GTO, Dr Karamanavis, Fraunhofer FHR*" in the report by Dr Karamanavis, Fraunhofer FHR.

TUMBLING RATES CONCLUSION

With regards to the observed tumbling behaviour, large GEO-stationary satellites show acceptable tumbling rates. Their rotation is low, so a connecting approach of a recycling space tug would be feasible. The successful *MEV-1* mission in early 2020[137] and *MEV-2* in 2021[138] are the best evidence of this assumption.

The upper stages in GTO tend to rotate faster than originally expected. Fortunately, there are several objects with "acceptable" rotation periods of 10 seconds and more. For these objects, approaching and connecting with today's technology, such as the *MEV* missions, seems feasible. As the observations of Mr. Schmalz, Castelgrande show, that the rotation period of the upper stages in GTO increases over the years, the number of recyclable upper stages will naturally increase over time.

Faster rotating upper stages would have to be detumbled first, which would require additional steps as part of the recycling mission. Worldwide, various concepts for detumbling upper stages in space have been researched and developed. A very promising solution is based on eddy current induction, which slowly detumbles contactless the upper stages from a safe distance.[139] This method is described below in the chapter "*Overview of Detumbling Technologies*".

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[137] First Docking of Mission Extension Vehicle with Intelsat 901 Satellite - Northrop Grumman

[138] Northrop Grumman MEV-2 successfully docked to a satellite to extend its life - Space.com

[139] Eddy currents applied to de-tumbling of space debris

SELECTION CRITERION 3: ASSOCIATED RISKS

In addition to the advantages of raw material recycling, the removal of (uncontrolled) space debris will reduce the associated risks of these objects for all other (space) activities. In general, these associated risks of could be categorized into collision risks with other space objects,[140] impacts of the object or its fragments with humans or objects on the Earth's surface[141] and environmental risks (not only) from toxic components at surface impact or during atmospheric ablation on re-entry.[142]

IMPACT RISKS

Every day, rocket stages, satellites, or fragments re-enter the Earth. Medium-sized objects, such as 1m or higher, re-enter about once a week, while on average two small, tracked debris objects re-enter per day. Large objects, such as heavy scientific satellites, re-enter the Earth's atmosphere only sporadically in one year. In general, re-entering objects represent only a marginal risk to people or infrastructure on the ground or to aviation.[143]

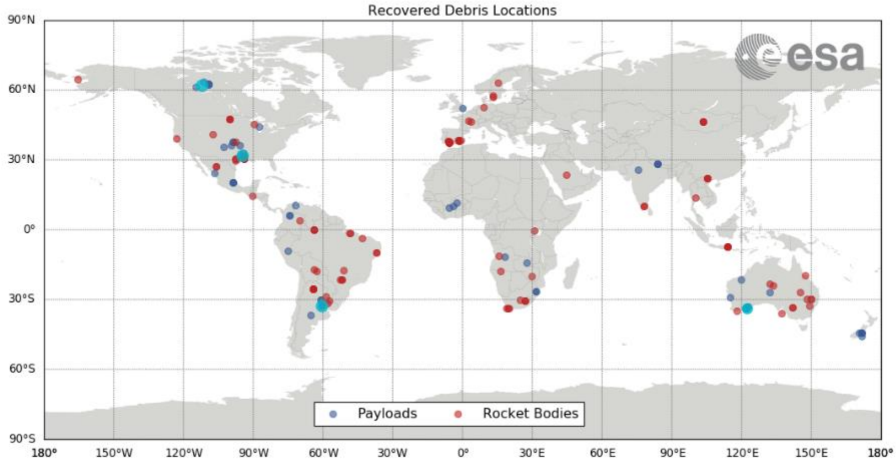

Figure 17: Location of recovered re-entry debris fragments worldwide (ESA, (143))

ENVIRONMENTAL RISKS

The environmental impact of space debris on the Earth` atmosphere is not yet very well understood. In the long-term, debris could pose a significant risk to the higher atmosphere due to the unknown chemical reactions that occur during its ablation when it enters the atmosphere.[144] Although the total mass of "burned" material per year is small, it will sum up over decades and centuries and should not be ignored. Instead, detailed atmospheric research should begin sooner than later to fully understand the long-term effects, especially if this method remains the recommended solution to the exponentially growing number of space debris in LEO.[145]

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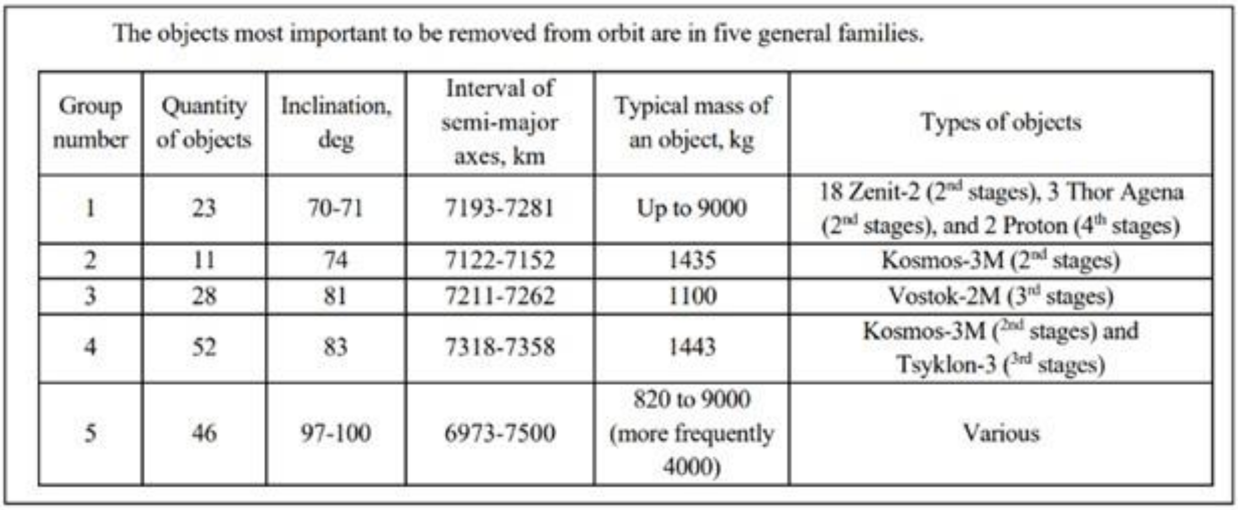
[140] Iridium 33/Cosmos 2251 Collision - CelesTrak
[141] The role of reentries - ESA & UNOOSA
[142] Nuclear Incidents in Space - Space4Peace
[143] Reentry and Collision Avoidance - ESA
[144] How Do Rocket Launches and Space Junk Affect Earth's Atmosphere? - Space.com
[145] Falling to Earth takes a long time - ESA & UNOOSA

COLLISION RISKS

Collision risks are the biggest risks of uncontrolled space debris. Especially in crowed orbits such as LEO, space debris becomes an annoying problem,[146] which already causes evasive manoeuvre costs of 14-million-euro-per-year for satellite operators.[147]

Of all space debris objects, spent upper stages are the most dangerous objects. Of more than 290 recorded in-orbit-fragmentation-events, only a few collisions were identified, while most of the events were explosions of spacecraft and upper stages. These fragmentation events are believed to have generated a population of about 750,000objects larger than 1 cm.[148]. Rocket upper stages are particularly worrisome, as their size can produce many more objects.[149] A breakup of a single Japanese H-2A upper stage in 2019 caused more than 70 pieces of tracked debris. One of them came close enough to the *International Space Station* (ISS) in September to justify a manoeuvre of the station.[150]

At the *71st International Astronautical Congress 2020*, an analysis of the 50 "*statistically most concerning*" debris objects in low Earth orbit was presented, with 78% of the objects on the list being rocket bodies. Their elimination would significantly reduce the overall risks to all space activities.[151]



The objects most important to be removed from orbit are in five general families.

Group number	Quantity of objects	Inclination, deg	Interval of semi-major axes, km	Typical mass of an object, kg	Types of objects
1	23	70-71	7193-7281	Up to 9000	18 Zenit-2 (2nd stages), 3 Thor Agena (2nd stages), and 2 Proton (4th stages)
2	11	74	7122-7152	1435	Kosmos-3M (2nd stages)
3	28	81	7211-7262	1100	Vostok-2M (3rd stages)
4	52	83	7318-7358	1443	Kosmos-3M (2nd stages) and Tsyklon-3 (3rd stages)
5	46	97-100	6973-7500	820 to 9000 (more frequently 4000)	Various

Table 5: Most important space debris objects to be removed from orbit (McKnight, (151))

While most of the upper stages of the above LEO list above are non- European debris, European launchers have polluted our orbit with over hundred rocket body objects in recent decades. However, since they are positioned in GTO, they were not considered for the above list.

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[146] The cost of avoiding collision - ESA & UNOOSA
[147] Space Debris – Space19+
[148] About space debris - ESA
[149] Upper stages top list of most dangerous space debris - Spacenews.com
[150] Space station maneuvers to avoid debris - Spacenews.com
[151] Identifying the 50 Statistically Most Concerning Derelict Objects in LEO

EUROPEAN LAUNCHER TYPES

Three types of European launcher are currently in use: the Ariane (family), Vega and Soyuz.

Soyuz and Vega use upper stages, which usually deorbit after a typical launch mission with a deorbit burn of their engines. Soyuz as well as Vega are therefore considered to be fully compliant with the regulations of the IADC guidelines for the mitigation of space debris.[152] Only a single Vega upper stage, (called *AVUM)* and two Vega adaptors (called *Vespa*) have remained in orbit so far. One of these *Vespa* is the removal-target of the planned European *ClearSpace-1* mission.[153]

Figure 18: European Launchers (not the same scale, Handschuh et.al., (155))

But the upper stages for the Ariane launcher family were not normally re-ignitable and therefore remained in orbit.[154] This will not change before the next generation Ariane 6. Most Ariane upper stages remained in a *highly elliptical orbit* (HEO), especially in GTO. Estimates of the lifetime of GTO debris elements show that the existing upper stages will remain in orbit for several decades.[155] Since these orbits span the range from LEO to MEO to GEO with an orbit period of 10 to 12 hours, the uncontrolled upper stages will often cross the trajectories of many other objects at different heights with the associated (high) collision risks. The removal of the upper stages from the GTO would therefore significantly reduce the associated collision risks.

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[152] Space debris mitigation measures applied to European launchers

[153] ESA commissions world’s first space debris removal - ESA

[154] Only the Ariane 5 EPS upper stage could be restarted up to 4 times. Nevertheless, after their missions, several EPS upper stages remained in higher orbits, such as MEO.

[155] Estimation of Lifetime for Launchers Debris in Geostationary Transfer Orbits

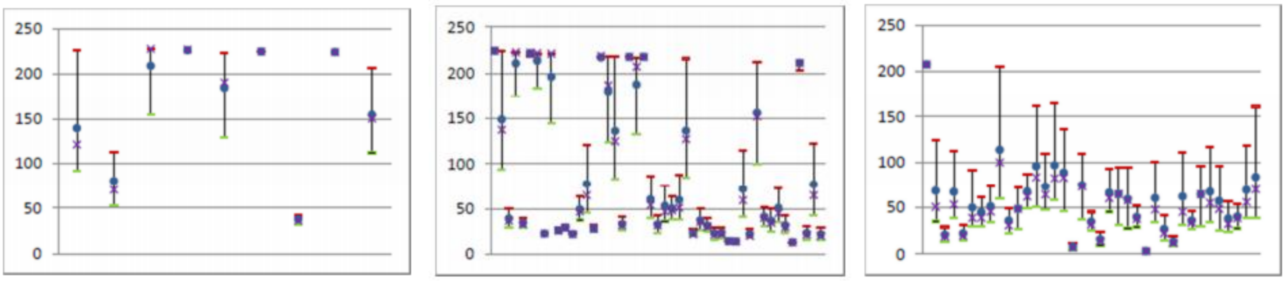
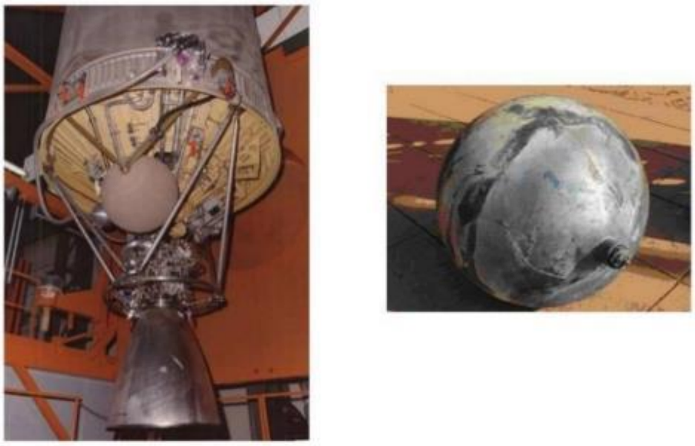


Figure 19: Total lifetime for Ariane upper stages in years.

Left: Ariane 1, 2, 3. Middle: Ariane 4. Right: Ariane 5 (Handschuh et.al., (155))

In addition to the collision risks in orbit, the re-entry risks for European upper stages were assessed in numerous studies. New modelling technologies have been developed for better risk predictions,[156] and it appears, that most of the upper stages will breakup at an altitude between 80 and 52km. Upper stages have higher impact risks than GTO satellites, which will never re-enter naturally, or satellites from LEO mega constellations, which are much smaller and therefore usually "burn" completely on re-entry. But the overall impact risk of the upper stages is still moderate, as only certain fragments such as tank segments, shown below, will reach the surface.



Helium sphere before and after flight

Figure 20: Titanium Helium pressure sphere hit a house in Kasambya, Uganda.[157]

CONCLUSION SELECTION CRITERIA

Based on the identified recycling scenario of raw material recycling for space manufacturing and the identified use case of aluminium recycling for a lunar ground station from Part 1, the most suitable space debris elements for Europe should be derelict upper stages in GTO. They have the highest amount of recyclable material per object of more than 2 tonnes of aluminium for the Ariane 5 ESC-A model, the best ratio of recyclable raw material compared to the total weight of >60% and represent more than 60 identical objects still in space. Their location is the highly elliptical orbit GTO, which requires little more energy for the remaining lunar transit than for large GEO-located satellites.

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[156] Breakup prediction under uncertainty: application to Upper Stage controlled reentries from GTO

[157] Study of spacecraft elements surviving an atmospheric re-entry

Compared to satellites in GEO or MEO[158], the associated risk of GTO upper stages to other space activities is much higher, as they often cross many different orbits from LEO to GEO and most of them will remain in orbit for decades to come. They also have a certain risk of impact on their final re-entry. Removal of these high-risk-elements should be considered, and the recycling option presented could be a compelling reason for this.

Only the identified tumbling rates speak for GEO satellites: in general, they rotate in lower periods than GTO upper stages and should be easier to approach. But dedicated upper stages with rotation periods of more than 30 seconds have been identified and effects observed, that tend to naturally lower the rotation period of the upper stages over time, resulting in more potential recycling targets.

In the end, more than 150 tonnes of aluminium were identified in GTO in the form of the European Ariane 5 ESC-A upper stages, which were waiting for a second life as construction material on the Moon.

VALIDATING UPPER STAGE TUMBLING BEHAVIOURS FROM SPACE

To validate the derived tumbling and rotation models in space, a precursor mission in GTO is proposed. A visual inspection of a derelict upper stage should occur, which would not only help to determine the exact tumbling and rotational movements of the upper stage, but also to inspect and observe the space aging effects of the upper stage material after being exposed to space for several years. The expected results would be beneficial for any space material research in general.[159]

The proposed precursor mission would allow testing components for approaching objects in complex trajectories such as GTO. Dealing with such complicated situations would be beneficial not only for recycling missions but also for all types of space servicing missions in the future. Even scientific deep space missions to approach and land on smaller moons or asteroids would benefit from these experiences. Ideally, such a precursor mission is carried out as a (university) research competition, which makes it possible to compare different approaches to identify the most efficient solution. By offering a free slot in one of Ariane 6`s planned GTO rideshare (test) launches, ESA could support this precursor mission concept with an affordable investment. [160]

As part of this study, Orbit Recycling carried out a preliminary analysis of such a precursor mission. The aim was to estimate the delta-v requirements of a satellite launched into GTO with a rideshare mission to approach the derelict Ariane 5 upper stage with NORAD ID 31308 (2007-016C). Several realistic assumptions have been made regarding the GTO-launch orbit of the rideshare mission on an Ariane 6 from Kourou. A scenario for the two orbits was defined with an initial difference of 0.6421° for RAAN, 5.6049° for AOP, 0.2432° for the inclination, 10.6423 km for perigee altitude and 3.534,2201 km for the apogee altitude to estimate the total delta-v budget for the precursor mission.

Max Manthey from the group of Merlin Barschke and Prof. Bardenhagen at TU Berlin, Germany designed a rideshare mission, in which a small satellite (called *Tubix*) is launched into GTO with a slightly higher apogee than the upper stage target. The higher apogee leads to a longer orbital period, which allows the precursor satellite to "*wait for the upper stage*" during the initial *launch and early orbit phase* (LEOP) of its mission.

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[158] Modeling of Breakup Events in Medium Earth Orbit

[159] Orbital space ageing tests offered for space age materials - ESA

[160] Arianespace's "GO-1" mission will provide small satellites with a direct flight to geostationary orbit

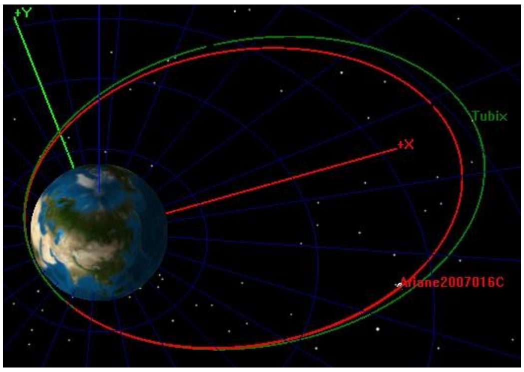

Figure 21: Orbit of precursor satellite (green) and upper stage target (red) (Manthey, TU Berlin)

The second mission step is the adjustment of the orbital inclination. This is necessary because the parameters of the rideshare mission are usually defined by the primary payload of the shared launch and do not fit into the target orbit. The orbital inclination is followed by the gradual phasing of the precursor satellite with the target object, in this case the Ariane 5 upper stage. The final rendezvous manoeuvres complete the target approach and guarantee a similar orbit and velocity in all dimensions for the precursor satellite and the target. Table 6 summaries the mayor mission steps from Manthey. After 95 hours or 4 days, the precursor satellite has arrived at the upper stage target.

Epoch in UTC	HR/MIN/SEC	Mission steps
17 Sep 2020 14:13:38	00:00:00 +00:02:20	Lift-off Ariane 6 from Kourou
17 Sep 2020 14:15:58	00:02:20 +00:01:01	Booster (EAP) separation
17 Sep 2020 14:16:59	00:03:21 +00:05:29	Fairing jettisoning
17 Sep 2020 14:22:28	00:08:50 +00:16:10	EPC burnout and separation
17 Sep 2020 14:38:38	00:25:00 +00:05:00	Upper stage burnout
17 Sep 2020 14:43:38	00:30:00 +00:15:00	Separation of precursor satellite
17 Sep 2020 14:58:38	00:45:00 +67:44:16	Start of *Launch and early orbit phase* (LEOP) and *coasting phase*
20 Sep 2020 10:42:54	68:29:16	Start inclination change manoeuvre
	+00:03:38 +15:40:00	End of manoeuvres
21 Sep 2020 02:26:32	84:12:54	Phasing manoeuvre 1.0
	+00:07:11 +04:58:13	End of manoeuvre
21 Sep 2020 07:31:56	89:18:18	Phasing manoeuvres 2.0 (V and B part)

	+00:05:26 +03:28:52	End of manoeuvres
21 Sep 2020 11:06:14	92:52:36	Correcting manoeuvres (N part)
	+00:11:29 +01:12:37	End of manoeuvres
21 Sep 2020 12:30:20	94:16:42	Rendezvous manoeuvres
	+00:22:16 +00:31:58	End of manoeuvres
21 Sep 2020 13:03:42	94:50:04	Approach of target achieved

Table 6: Precursor Mission Steps (Manthey, TU Berlin)

To calculate the mission manoeuvres and the required delta-v`s, Manthey used the *General Mission Analysis Tool* (GMAT), which was provided by NASA in its revision R2020a. The total delta-v requirements of the calculated trajectory can be summarized as follows:

Manoeuvre	Required Δv
Inclination change	7.2638 $^{m}/_{s}$
Begin of Phasing	14.4614 $^{m}/_{s}$
End of Phasing	40.0680 $^{m}/_{s}$
Rendezvous	111.1225 $^{m}/_{s}$
Total $_{\text{Manoeuvres}}$	**172.9157** $m/_{s}$

Table 7: Delta-v Overview of Precursor Mission (Manthey, TU Berlin)

To avoid unnecessary space debris, the precursor satellite should deorbit itself after the mission. For this purpose, the perigee should be lowered to an altitude of less than 170 km. According to Manthey, the manoeuvres resulted in the following delta-v requirements:

Parameter	Symbol	Value	Unit
Length of manoeuvre in -V-direction	Δt	296.520	s
Achieved delta-v change	Δv	10.8226	m/s
Finale perigee height	z_p	100	km

Table 8: Precursor Deorbit Manoeuvre (Manthey, TU Berlin)

Manthey concluded, that the Aerojet Rocketdyne's *MPS-135-4U* engine would be a suitable propulsion solution for a precursor mission based on a 30 kg-class satellite. The *MPS-135-4U* can be used with a "green" propellant, that complements the sustainable character of the entire mission concept.

In summary, a GTO precursor mission with various small satellite busses in the range of 30 kg seems feasible. The required delta-v of around 172 m/s is demanding but can be achieved with existing propulsion solutions. The feasible results of such a visual inspection mission would be beneficial for both future space servicing missions and a better understanding of object tumbling behaviour in GTO.

RECOMMENDED NEXT STEPS

The selection criteria used to identify the best recycling targets could be further improved by the following proposals:

1. The available data on the composition of space objects are still limited. As mentioned earlier, this data is crucial for any future waste treatment. Efforts should be considered to extend the existing data sets such as DISCOS with detailed material information, provided by the manufacturers. If necessary, the data can be encrypted and anonymized until it is needed for a dedicated space mission.
2. Like in the LEO environment, the associated risks for GTO objects should also be examined and modelled in more detail. GTO upper stages cross many other object trajectories and due to their size, any fragmentation event through explosions or collisions would produce a large amount of secondary space debris objects, that expose all other space objects to unpredictable risks.
3. The rotation behaviour of upper stages in GTO should be explained in more details. A better understanding of their tumbling behaviour would simplify any upcoming recycling mission.

With regards to rotational behaviour, European research is proposed as a specific follow-up of this study. The light curve measurements already and continuously collected by the Castelgrande Observatory and its partner network are to be combined with the capabilities of the Fraunhofer FHR TIRA instrument. This would allow Europe to generate a unique data pool of different GTO data sources. A promising concept proof for such a combination was presented at the *8th European Conference on Space Debris 2021* by Mariani, Santoni, et.al. [161] as well as from Apa, Bonaccorsi, Pirovano and Armellin.[162]

The generated data will be used as a basis for object tumbling modelling by renowned institutes such as the *Astronomic Institute of the University Bern* (AIUB) around Professor Zimmerwald[163] or the *Institute of Technical Physics* of Prof. Dekorsy, DLR, in Stuttgart.[164] Initial studies by Antón, McNally, Ramirez, Smith and Dick, who use machine learning to characterize objects from their lightcurve pattern,[165] show encouraging results. Combined with the data collected by Castelgrande and FHR TIRA, machine learning could be an ideal way to understand the tumbling of space objects in detail. The derived tumbling rates could be further validated by illuminated 3D models in an experimental setup.[166] Finally, a GTO-precursor mission should validate the theoretical tumbling rates and inspect the upper stages for any visible damages or space aging effects after being exposed decades to space radiation.

The results would allow a good understanding of object tumbling behaviour in GTO, which is relevant not only for any upper stage recycling mission but also for stranded satellites during a failed GEO launch.

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[161] Enhancing the knowledge on space debris attitude and position combining radar and optical observations

[162] Combined Optical and Radar Measurements for Orbit Determination in LEO

[163] Related publications from AIUB

[164] Institute of Technical Physics - DLR

[165] Artificial Intelligence for Space Resident Objects Characterization with Lightcurves

[166] Optical signature analysis of tumbling rocket bodies via laboratory measurements - NASA

OVERVIEW OF DETUMBLING TECHNOLOGIES

CHAPTER SUMMARY

If the upper stage targets drift stably in space, they could be approached directly by a recycling space tug and transported to the Moon. However, if they were to tumble, they would first have to be stabilized. In recent years, research has been carried out on this topic. In various experiments, the functionality of an eddy current break was demonstrated, and corresponding space concepts were designed. Alternative solutions are also available, that lead to the fair conclusion, that the detumbling of upper stages in GTO could be considered "*technically feasible with today`s technology*".

The problem of detumbling uncooperative targets in space is not limited to upper stages. In recent years, various (theoretical) space missions have been discussed, in which detumbling of large objects in space was a problem that had to be solved. The most prominent case for ESA is the *e.deorbit* mission with the *ENVISAT* satellite as its target, which is to be detumbled.[167]

Under ESA contract No. 4000113022/ 14/NL/MV, GMV analysed different detumbling methods.[168] Different concepts, from contact-based to contactless, were compared. The image below from the GMV study summarizes these methods according to the type of interactions:

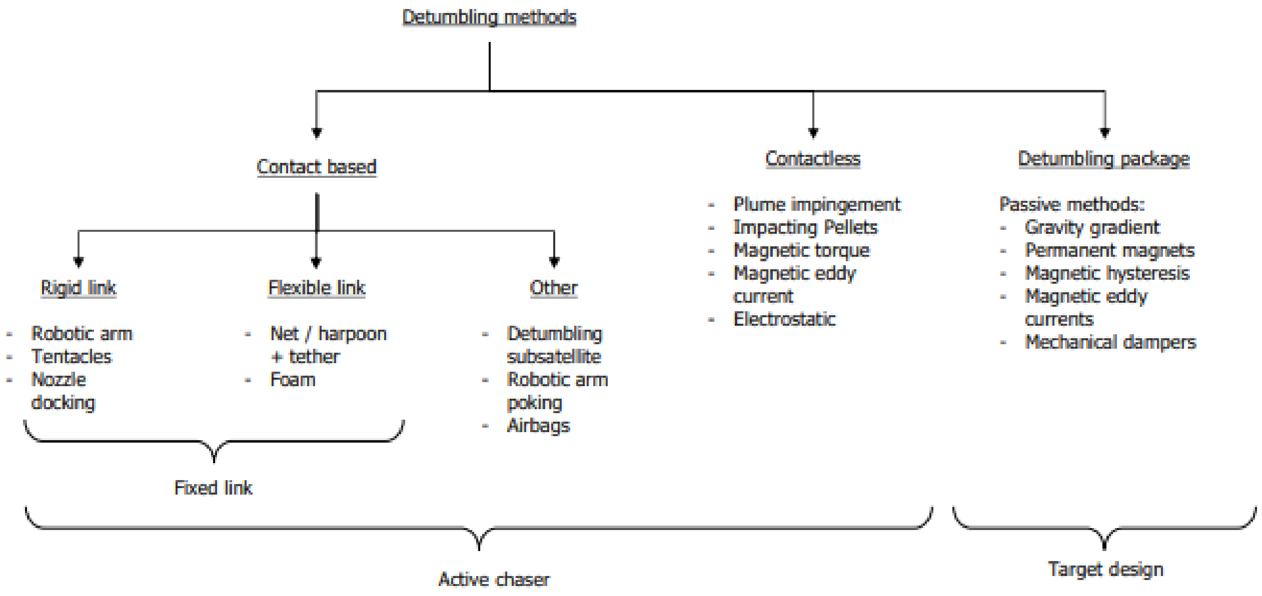

Figure 22: De-tumbling methods organized according to type of interaction, GMV Study (168)

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[167] ESA's e.deorbit debris removal mission reborn as servicing vehicle - ESA

[168] Investigation of Active Detumbling Solutions for Debris Removal - ESA

At the time of the GMV study, contactless detumbling solutions had a lower *Technology Readiness Level* (TRL) than contact-based solutions such as a robotic arm, which became the proposed solution for the *ENVISAT* case.

In the meantime, more detailed studies have been conducted on contactless eddy current break solutions,[169] many of which directly target (Ariane) upper stages.[170] These studies show the general feasibility of this concept: via large coils attached to a stabilized chaser satellite, an eddy current is inducted in the non-ferromagnetic body of the upper stages, causing its spinning speed to decay over time. The chaser satellite will follow the upper stage in a secure distance. Depending on the accuracy of its distance and spatial position to the target upper stage, the decay-rate can be shortened or will increase.

Sugai, Abiko et. al. conducted detailed experiments with eddy current breaks supported by JAXA.[171] Their target model, which simulates the *Himawari 5* satellite, had a diameter of 2.15 m, a height of 3.54 m, a mass of 345 kg and rotated at 100 rpm. As expected, the experiments showed a significant decrease in the angular momentum vector.

Other scenarios imagined a magnetic field generated from ten meters with respect to the target`s *Centre-Of-Gravity* (COG) to reduce the target`s tumbling rates below the threshold of < 1 degree/sec. The detumbling coil has been designed to have the maximum radius of 1.65 meters allowed by the Ariane-5 SYLDA fairing, which would be comparable to the upcoming Ariane 6 launcher.

In the paper of N. Gomez and Dr Walker (169), the case of an Ariane 5 EPS upper stage in GTO with a total mass of 3 tonnes was analysed. This mass approaches the dry weight of the Ariane 5 ESC-A upper stage, the recommended recycling targets of this study. The main difference from Gomez and Walker is the total conductive mass, which for the EPS stage is much smaller than the ESC-A type.

Nevertheless, the results for the EPS show, that the target angular velocity could be effectively reduced over the calculated period of 60 days, that the manoeuvres performed by the chaser would be in the order of tenths of millinewtons and that the relative motion control is limited to planar relative positioning.

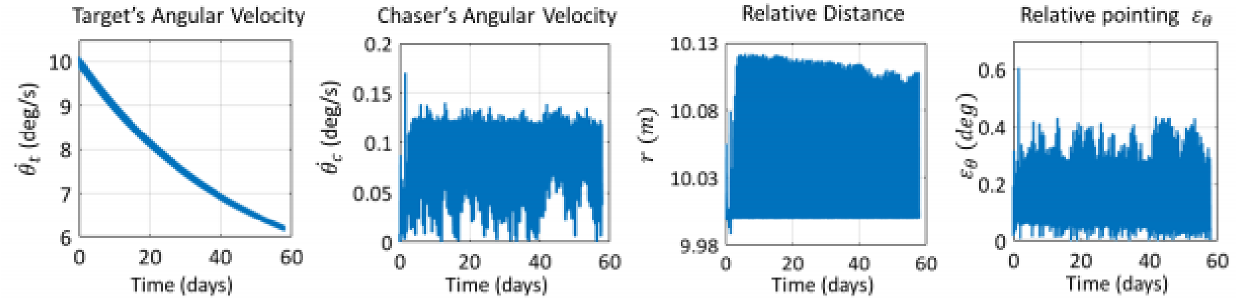

Figure 23: Kinematics of the chaser-target systems (Gomez, Walker, (169))

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[169] Guidance, navigation, and control for the eddy brake method

[170] Study on the eddy current damping of the spin dynamics of space debris from the Ariane upper stages

[171] Detumbling an uncontrolled satellite with contactless force by using an eddy current brake

One solution to shorten the total detumbling time would be to divide the detumbling phase into two different steps:

- The first step would be a contactless eddy current break, until an angular rate of less than 5 degrees/sec is reached. This could be done with a dedicated, GTO--operating "*detumbling chaser*" with the sole purpose of rapidly approaching tumbling upper stages in GTO to slow them down to the desired rotational speed. Once this goal is reached, it approaches another target in a different orbit and begins the next detumbling. This split approach allows an optimal design for the chaser satellite.
- The second step would be the orbital and rotational synchronization of a separate "*recycling tug*" to establish a secure physical connection between the tug and the target. The recycling space tug would be launched after the targeted upper stage has been stabilized by the chaser and could grab the slow tumbling upper stage after synchronizing its movements in space. Although this split would not reduce the total time to stabilize the upper stage, it would reduce the individual mission times to acceptable lengths.

In summary, the main advantage of a contactless detumbling technology via an eddy current method is its relatively safe execution: there is always a safety distance between the chaser and the target. In addition, there is no need for complex synchronization manoeuvres to align both spaceships.

Compared to plume impingement, eddy current will not release space contamination via particles, which must theoretically be considered as additional space debris elements with their own collision risk. Compared to LASER-based detumbling, the active range of eddy current induction is much smaller. Although this could be considered a disadvantage, it also contributes to the overall safety of the solution: Theoretically, a space-based LASER solution could negatively affect an uninvolved target with its elongated LASER beam. Without deflection by an atmosphere, the (reflected) LASER beam could damage optics or instruments of other satellites, while the electromagnetic field of the chaser coils would not reach much further than the target itself.

A DETUMBLING CHASER SATELLITE

Based on Manthey`s calculations, Orbit Recycling envisioned a chaser satellite that detumbles upper stages in GTO. The concept follows the JAXA *Commercial Removal of Debris Demonstration project* (CRD2) to remove an H2A upper stage with comparable size and weight to the Ariane 5 ESC-A upper stage.[172]

Like Orbit Recycling, JAXA is planning a precursor mission to approach and inspect the upper stage with a spacecraft manufactured and operated by Astroscale.[173] With the development of JAXA/Astroscale, ESA/*Clearspace-1* ADR mission and the successful *MEV-1* and *-2* missions, it`s fair to say that the technology required for a safe approach, as well as the rendezvous and proximity capabilities, will be available at least at the time of the planned chaser mission.

Astroscale estimates a dry weight of ca. 180 kg (see 123) for its LEO precursor mission satellite. For the GTO chaser, this weight must be increased by the weight of the coil structure, by the weight of the larger propellant tanks due to the higher delta-v requirements of the longer GTO chaser mission, as well as by increased radiation

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[172] JAXA Commercial Removal of Debris Demonstration (CRD2)
[173] Astroscale Selected as Commercial Partner for JAXA's CRD2 Project - Astroscale

shielding for the electronic components, since the chaser operates all the time in GTO with its extensive radiation exposure, while often passing through the radiation belt.[174]

For this first feasibility assessment, a dry weight of 500 kg is estimated. This allows the chaser to be launched either on a Soyuz launcher or as a secondary payload on an Ariane 62 or 64 in GTO. Like Manthey`s precursor satellite, it would approach an upper stage in GTO over a period of few days and then detumble it over a further 60 days using the eddy current methodology with 1 or 2 coils.

While Manthey estimates 180 m/s for approaching the upper stage, Orbit Recycling adds an additional margin and calculates at 270 m/s to reflect the wider variabilities between the different orbits of the upper stages. Equipped with a monopropellant propulsion with an ISP of 220 and using the rocket equation for simplified total weight assessment, a 3,000 kg chaser satellite can execute 12 missions over a 3-year period to detumble 12 upper stages in GTO. Alternatively, a 1,700 kg chaser can perform 8 missions over 2 years. Both chasers will still have enough propulsion left for a deorbit manoeuvre.[175]

With an estimated price of 25 million euro per chaser, additional launch costs of 40 million euro per chaser in GTO and mission operation costs of 2 million euro per year, total costs of 70 million euro would be incurred for 8 to 12 upper stages: This adds up to 6 to 9 million euro per upper stage with a recycling potential of 2.2 tonnes of aluminium per upper stage or 2,730 to 4,090 euro per kilogram.

RECOMMENDED NEXT STEPS

Contactless detumbling methods are promising solutions, not only for the specific case of upper stage recycling. Any space servicing mission with an uncooperative target, if it is a satellite released in a false orbit or an out-of-control astronaut capsule, would benefit from such detumbling technology. It is proposed to carry out own experiments and studies here in Europe, which are driven by ESA, with different coil designs in terms of diameter and conductor material, to develop an optimal generic detumbling tool that could be used for different scenarios in the future.

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[174] Radiation: satellites’ unseen enemy - ESA

[175] All calculations include an additional 15% propellant margins for each 270m/s mission to ensure the required detumbling maneuvers for the upper stages. A table showing the calculation can be found in the appendix under “*Delta-v Calculations for Chaser Tug*”.

OVERVIEW OF GRIPPING TECHNOLOGIES

CHAPTER SUMMARY

Several studies around the world investigated the technical feasibilities of robotic arms and manipulators to capture larger space debris items under different conditions. The results show that the capturing of (detumbled) upper stages should be "*feasible with today`s technology*".

However, the preferred gripping point varies from mission to mission. In the US, the nozzle at the back of the target object appears to be the preferred access point, while JAXA/Astroscale goes to the *payload attach fitting* (PAF) at the top of the chosen target object. With its *ClearSpace-1* mission, Europe embraces the entire target object with four large arms.

Currently, Orbit Recycling favours a stinger-like solution aimed at the upper stage nozzle, as this connection point would not only be the same for the 60+ Ariane 5 upper stages but for 80 additional upper stages from earlier Ariane versions. This preference can change after completing a gripping research project together with TU Berlin, Germany at the end of 2021.

While the detumbling of space objects can happen contactless, gripping them requires a (secure) physical connection. In the past, various technologies have been investigated and partly used in space. Various robotic arms or manipulators have been used and images showing the *Space Shuttle* with the *Hubble Space Telescope* or the ISS capturing a supply vessel may be familiar to the reader.

Figure 24: Hubble Space Telescope gripped by space shuttle Columbia's robotic arm (NASA)

Figure 25: ISS with its CANADARM capturing a supply vessel (NASA)

For space debris targets, a robotic arm is therefore a valid option. But due to weight and cost constraints, a solution for a recycling tug will look different from the massive arms shown in the pictures above.

During the preparation of the *e.deorbit* mission to remove the *ENVISAT* satellite from orbit, ESA carried out its own research on such gripping technologies together with the European space industry (see 7). Various consortia proposed own designs and developed the first prototypes to be tested in laboratory environments.

Airbus UK developed the *Lightweight Advanced Robotic Arm Demonstrator* (LARAD) manipulator.[176] OHB Germany produced a comparable solution.[177] At the *71st International Astronautical Congress* (IAC) in October 2020, Wang, Zhou et. al. presented a study on the "*Capture and Stabilization Strategy for Large Tumbling GEO Debris Removal Using Space Robotic Manipulator System*".[178] One of the biggest challenges was the difficulty of approaching the target object without colliding with its solar arrays or antennas, while synchronizing the movements between the capturing space tug and the target object. Fortunately, upper stages have neither, allowing a much easier approaching.

In addition, the angular momentum between the tumbling target with its heavy weight and the capturing space tug could become a mechanical problem for the manipulator. This aspect was investigated by Vyas, Jankovic and Kirchner from the *German Research Centre for Artificial Intelligence (*DFKI-RIC), which was published at the IAC in 2020 under the heading "*Momentum Based Classification for Robotic Active Debris Removal*".[179] Several target objects with different dimensions and weights were analysed with regards to the angular momentum which is expected to occur with few potential robotic gripping arms. The paper provides a new method for the "*Momentum-Based"* classification of space debris that can be used to improve the selection of an ADR capture method, and it showed that the currently available space-flown robot manipulators could absorb the angular momentum of various upper stage debris.

If the target object shows low rotation behaviour, e.g., because it has been first detumbled, light robotic arms could be used for capturing the target. At IAC 2020, Nishida, Kobayashi et. al. presented a "*Study of Light Robot Arm for Space Debris Capture with Buffer Function*",[180] which was developed for capturing a Japanese H2A upper stage. In summary, the previous studies of robotic arms and manipulators justifies the assumption, that gripping a (detumbled) upper stage is "*technically feasible with today`s technology*".

In addition to criteria for choosing the "right" robotic arm for the target, the concept of the gripping process itself has also been investigated in the past. The catchphrase would be "*capture before connect*", which means that before a physical connection is made between the space tug and the target, the target is somehow secured so it cannot escape, even if the initial connection approach fails. This could be achieved by encapsulating the access point with a physical structure and is explained in the following three examples.

For its CRD2 mission, JAXA and Astroscale envisioned a capture device called *HoKaku Kiko* (HKK). With its V-shaped structure and two independent arms, the capturing device is positioned in the *payload adapter fitting* (PAF) and expanded. The large overlapping "fingers" of the V prevent the PAF from escaping, even if the expansion of an arm would (partially) fail. At the *8th European Conference on Space Debris* in April 2021, an updated design for this gripping clamp was presented.[181] The image below from JAXA visualizes this concept.

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[176] Airbus Active Debris Removal Service
[177] OHB Debris Removal Concepts
[178] Capture and stabilization strategy for large tumbling GEO debris
[179] Momentum Based Classification for Robotic Active Debris Removal
[180] Study of Light Robot Arm for Space Debris Capture with Buffer Function
[181] Concept and Design of Robustness Improved Caging Based Debris Gripper

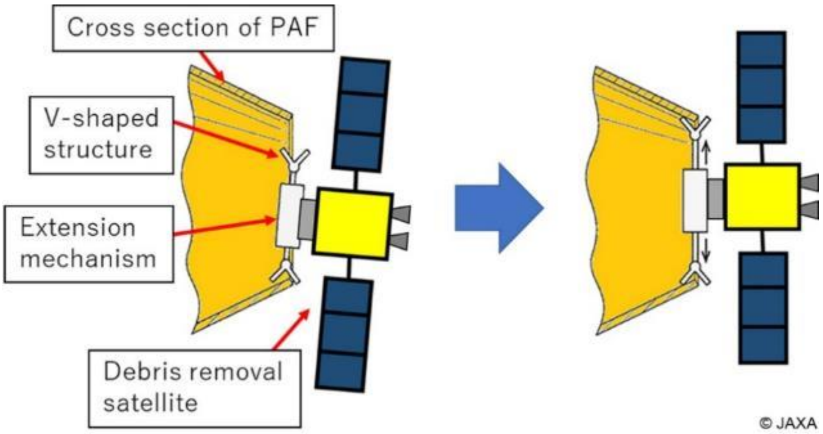

Figure 26: PAF capturing method of developed end-effector (JAXA, (181))

The second example is the NASA *Apogee Kick Motor* (AKM) capture device, which was used during the Space Shuttle mission STS 51-A[182] and described earlier in the chapter "*Reuse of Components*". Here, a stinger is carefully sticked in the nozzle throat of the target device, while at the same time, the nozzle itself is enclosed by larger structure to prevent the escape of the target. Due to the funnel shape of the nozzle and its large opening, it is easier to approach the target in this way than to surround a much thinner payload adaptor ring.

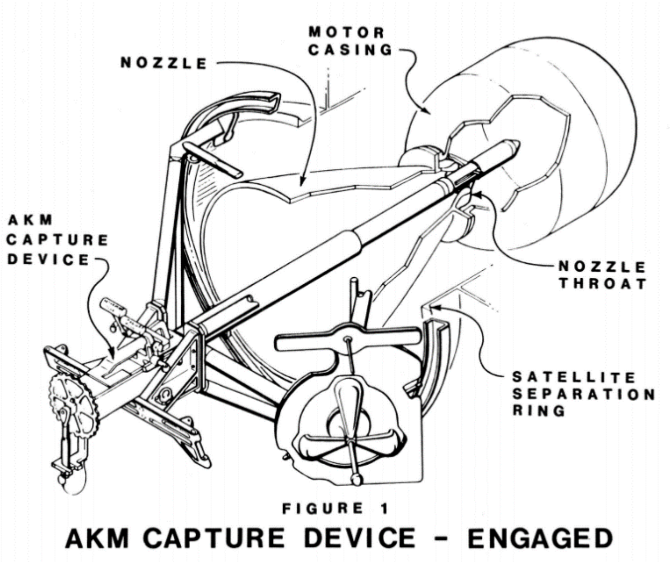

Figure 27: Apogee Kick Motor capture device (NASA, (182))

Besides capturing the satellites Westar and Palapa on the mentioned shuttle mission, the Northrop Grumman *MEV-1* and *-2* mission used a similar device to capture their target satellites at the nozzles, too. In addition, DeLuca et.al. describes a nozzle-based "*corkscrew*" (stinger) tool in the paper "*Large Debris Removal Mission in LEO based on Hybrid Propulsion*",[183] "*…which must be inserted inside the nozzle, centering the throat…*".

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[182] Apogee Kick Motor Capture Device - NASA

[183] Large Debris Removal Mission in LEO based on Hybrid Propulsion

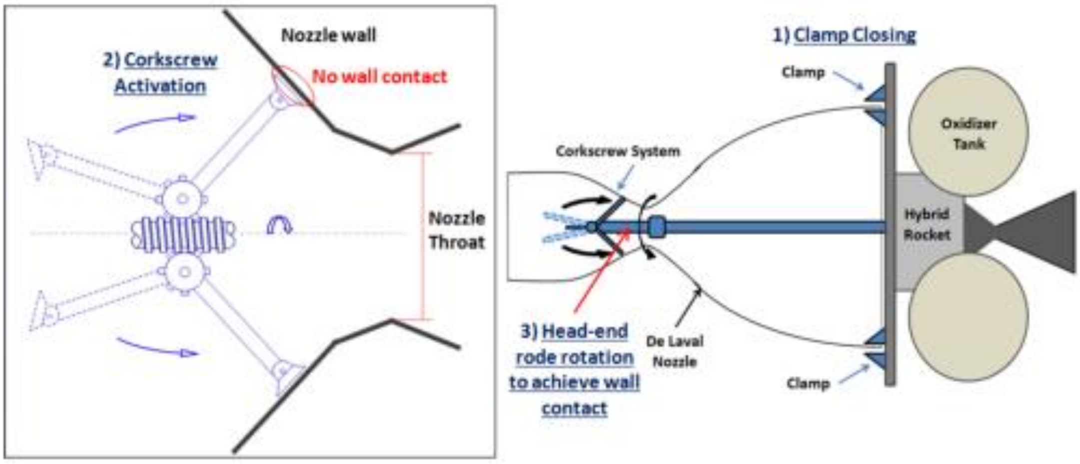

Figure 28: Nozzle-based "corkscrew" docking solution (DeLuca et.al., (183))

DeLuca et.al. analysed Ariane and Cosmos-3M upper stages as removal targets for their solution.

At the IAC 2020, Mayorova, Shcheglov and Stognii from Moscow presented a theoretical "*Analysis of the space debris objects nozzle capture dynamic processed by a telescopic robotic arm*", with the aim of removing old Zenit upper stages from orbit.[184] The focus was on a better understanding of the expected reaction forces and moments that arise when a passive robotic arm catches a large-sized space debris object of the Zenit upper stage, much larger and heavier than the Ariane ESC-A. By combining a robotic arm with a length of 13 m and the stiffness of the shock absorbers K=16 kN/m and K*=51.2 kN×m/rad, the maximum reaction force in the hinge between the robotic arm and the beam of the docking mechanism (joint D) will not exceed 2 kN. The moment of reaction forces in the translational joint will not exceed 19 kN×m. At the same time, the maximum stroke of shock absorbers in the joints will not exceed 0.06 m and 8 degrees, which makes this a viable solution for capturing an Ariane 5 ESC-A upper stage in GTO at its own nozzle.

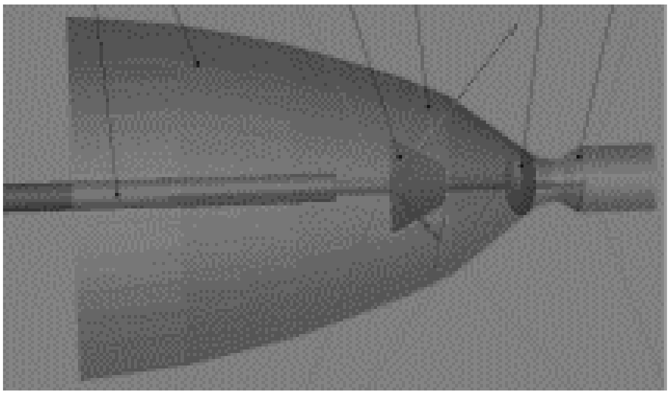

Figure 29: Nozzle capturing device (Mayorova, (184))

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[184] Analysis of the space debris objects nozzle capture dynamic processed by a telescopic robotic arm

The last example is embracing the whole object itself. This is the concept currently being discussed for the European mission *ClearSpace-1* (see 9). Here, the target object, the *Vega Secondary Payload Adapter* (VESPA), is fully embraced by the "*fingers*" of a large clamp, before it is captured, preventing the target from escaping. The image below from ClearSpace illustrates the concept.

Figure 30 ClearSpace' four-arms removal concept (ClearSpace, (9))

A similar concept was proposed by Airbus in 2015 in its *AGORA* mission concept,[185] which is discussed in more detail in the next chapter. There, a space tug design is discussed that targets an Ariane 5 upper stage in GTO and embraces the target with similar "*finger clamps*".

In addition to the manipulators discussed, ESA investigated net-based solutions and a harpoon concept as part of the *e.deorbit* mission concept (see 8). These options would start with a loose connection (net or harpoon wire) that would prevent the target from escaping the space tug. This loose connection might be sufficient to tug the object, although it would hardly be possible to push the target or perform a controlled rotation.

One result of the ESA study was that the net solution would be able to deorbit the target satellite. However, for a longer mission to the Moon with different requirements for its trajectory accuracy, a rigid connection between the target and the space tug seems to be required. Therefore, Orbit Recycling is not further investigating either a net-based or a harpoon solution for transporting the upper stage to the Moon. Instead, either a manipulator or a "*nozzle-stinger*" is proposed to grab the upper stages in GTO and securely connect the recycling space tug to the upper stage target.

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[185] Agora: Mission to demonstrate technologies to actively remove Ariane rocket bodies

RECOMMENDED NEXT STEPS

The optimal connection point at the target appears to be mission dependent. There are solutions for the top (payload adaptor), bottom (nozzle) as well the side (embracing the entire object). The nozzle would have the advantage of being the same for all Ariane 5 ESC-A upper stages, while the payload adaptor varied (slightly) between launches. In addition, the same nozzle (the HM7b engine)[186] was also used for the Ariane 4 and Ariane 3 upper stages, which provides more than 80 additional targets in GTO that could be removed for recycling.

Since Europe has already started with its own active debris removal mission to grab a large object in space, it is strongly recommended that this solution to-be-developed be evaluated in terms of its scaling potential. Currently, the chosen target is a light *Vespa* with less than 300 kg, while an Ariane 5 ESC-A upper stage weighs around 3,700 kg. Checking whether the European *ClearSpace-1* concept could be scaled by this factor >10 would be a cost-effective solution for the required gripping mechanism.

Alternatively, several activities around the world are actively developing solutions for grabbing large objects in space. Most of them target upper stages of their local regions. Several robotic arms and manipulators are commercially available, and chances are that the *European Robotic Arm* (ERA) will finally arrive on the ISS this year.[187]. A gripping solution for the Ariane 5 upper stages could be derived from these solutions as well.

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[186] HM7b Engine - ArianeGroup

[187] European Robotic Arm - ESA

CONCEPTS FOR A RECYCLING SPACE TUG MISSION

CHAPTER SUMMARY

Two different space tug concepts are discussed. A version based on the small Vega(-C) launcher offers affordable launch costs and would be theoretically feasible but results in an extremely long mission duration of more than 500 days. A direct launch into *Geo-Transfer Orbit* (GTO) has higher launch costs, but reduces the overall mission time, making this the preferred mission concept.

From GTO to the Moon, electric propulsion or water-plasma propulsion offer a good balance between flight duration and required propulsion mass and reduce the total weight of the recycling tug.

Several technological components of the recycling space tug have yet to be developed. Since the *ClearSpace-1* mission also requires several of them, most of the development will take place in the next few years. Nevertheless, it is important to check whether the *ClearSpace1* technology would also work in GTO and could be scaled to the higher mass of the upper stage targets.

Regardless of the actual design concept of the recycling tug, a space debris recycling mission would always have to fulfil the following mission tasks:

1) Launch into space. For Europe, this requires a launch on either the VEGA(-C) launcher in *Low Earth Orbit* (LEO) or on a Soyuz / Ariane 6x launcher directly into *Geo-Transfer Orbit* (GTO).
2) Transfer and phase into target orbit (GTO).
3) Rendezvous with the target object. If necessary and not done before, the target must be detumbled.
4) Capture of the target object.
5) Tug the target to the Moon.
6) Landing of the target on the Moon in a dedicated area.

The payload capabilities of the European launchers are given and limit the total weight of the recycling space tug. The Vega launcher is the smallest European launcher with the lowest launch cost but cannot place a payload directly in GTO. Instead, the payload is released in LEO and must approach the GTO itself. Up to 2,500 kg could be lifted in an orbit of 200 km, and it must be validated, that this is sufficient to complete the recycling mission of a GTO upper stage.

The Ariane 64 could launch up to 11,500 kg directly in GTO with the correct inclination of 6 degrees, like the orbit of the targeted upper stages. To validate the general feasibility of the recycling mission with this launcher, a very rough estimate is made: a space tug with a dry weight of 1,500 kg is anticipated to be launched in GTO. Using the rocket equation, the amount of propellant to the Moon for transporting the tug and an upper stage (weight: 3,700 kg) is calculated for a mono-propellant engine with an Isp of 220s. With the above-mentioned weight parameters and a delta-v for the GTO capture of 220m/s (incl. margin), a delta-v for the Moon transfer incl. orbit injection of 2,000m/s (incl. margins) and a delta-v for the landing manoeuvre of 114m/s (incl. margin), a total propellant mass of 9,750 kg is estimated. This results in a wet mass of 11,250 kg for the space tug, just within the launch capabilities of Ariane 64 in GTO. [188]

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[188] This rough estimate does not mean, that a tug with 9,750kg of propellant would exist or could be built.

It should be mentioned that this scenario would be the most weight demanding scenario for a Moon transfer, since neither the trajectory nor the propellant used has been optimized for the mission profile. Propellant types with higher Isp are available and / or lunar trajectories with lower delta-v requirements could be used, which would reduce the required amount of propellant and lead to a lower total weight of the space tug. Nevertheless, this initial assessment allows the fair assumption that theoretically a space tug could be launched on a European Ariane launcher, that could tug an old ESC-A upper stage from GTO to the Moon for recycling.

VEGA(-C) BASED CONCEPT

The motivation to use the small Vega(-C) launcher for the recycling space tug mission is derived from the ESA *e.deorbit* mission. Its target, the *ENVISAT* satellite, is in LEO, and the goal of *e.deorbit* was to deorbit and "burn" the satellite it in the Earth` atmosphere. The study showed that the Vega launcher would be suitable to launch the mission (see 8). Since Vega was considered a launcher for *e.deorbit*, the question arose whether the upper stage of Vega (called *AVUM*) could serve as a satellite platform itself, on which the capture and *Guidance, Navigation and Control* (GNC) equipment should be mounted as an "*AVUM proximity module"*. The motivation was also that the Vega upper stage already had a large bi-propellant propulsion system on board. The image below is from the *e.deorbit* study mentioned above.

Figure 31: Using VEGA`s upper stage as e.deorbit platform (ESA, (8))

This preliminary work by ESA was the basis for a feasibility study by Orbit Recycling and the *Institute of Space Systems* at the University of Stuttgart (IRS).[189] Tim Kochler from the research group led by Priv. Doz. Georg Herdrich and Manfred Ehresmann analysed, whether a space tug (ST) could be launched with a Vega-C rocket, approaching an Ariane 5 ESC-A upper stage in GTO, and tugging the upper stage not back to Earth, but further to the Moon. The specific requirements are summarized below.

1) Functional Requirements
    1. The ST shall rendezvous with an ESC-A upper stage in a GTO.
    2. The ST shall manipulate the position of the ESC-A so that it is within the capability of the ST to interact mechanically with the object.
    3. The ST shall transfer the ESC-A upper stage to the lunar environment.
    4. The ST should deorbit the ESC-A onto the lunar surface.
    5. The ST should reduce the impact speed of the ESC-A towards the lunar surface, so it breaks up in pieces.

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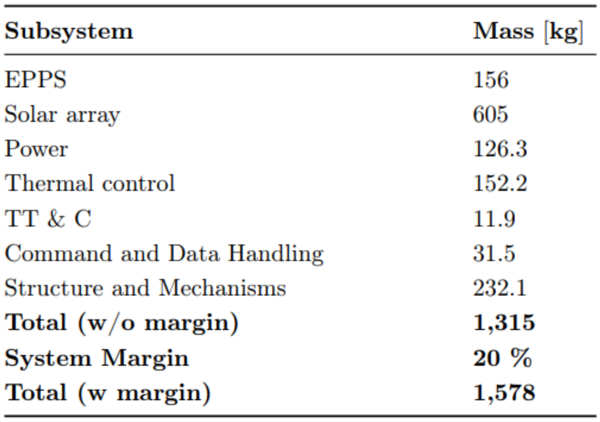
[189] *System Study for a Trans-lunar Space Tug for Upper Rocket Stage Debris*, Tim Kochler, Manfred Ehresmann, Priv. Doz. Georg Herdrich, IRS, IRS-20-S-039

2) Mission Requirements
    1. The ST should use an electrical propulsion system.
    2. The ST shall be able to target a 2000 m radius impact area within the Aitken Basin on the Moon.
    3. The ESC-A should strike the lunar surface in a way that leaves its parts in a combined solid state (un-evaporated or melted).
    4. The ST can hit the lunar surface together with its payload.
    5. No space debris should be created throughout the whole mission.
    6. No system shall be used that is hazardous to the lunar environment or the future use of the Moon.
3) Physical Requirements
    1. The ST should be launchable with an Arianespace Vega (Vega-C)
4) Design Requirements
    1. The ST including its components shall be producible in a small series.
    2. The ST including its components shall withstand solar and space radiation within the Earth-Moon system.
    3. The ST including its components shall be recyclable.
    4. The ST including its used technology shall be readily available today.
    5. The ST should be single failure tolerant against micrometeorite and space debris impacts.
    6. The structure of the ST should be made of Al2219.
5) Interface Requirements
    1. The ST shall dialogue with the upper stage of the launcher during launch.
    2. The ST shall mechanically interface with the ESC-A upper stage.
    3. The ST can dialogue with the Altitude and Vernier Upper Module (AVUM) for Attitude and Orbit Control System (AOCS) and main engine use.
6) Operational Requirements
    1. The ST shall be designed to be remotely controllable.
    2. The ST shall be designed to autonomously adjust its trajectory to match the specified orbital parameters.
    3. The ST shall be able to communicate to Earth when a line of sight given.
    4. The ST should be able to detumble the ESC-A in orbit

Figure 32: Vega-C based space tug design (Kochler, IRS)

Kochler's space tug is designed to remain connected to the AVUM+ upper stage of the VEGA-C throughout the mission. Only together they represent a complete spaceship with all necessary subsystems. Figure 32 visualizes this idea. The ESC-A upper stage, which the space tug is to pick up in orbit, is displayed to scale.

In his study, Kochler describes the space tug concept in more details. Table 9 lists the most relevant parts. Kochler proposes Xenon thruster as propulsion. The required solar panels would span an area of 90m² but could still fit into the Vega fairing volume.



Subsystem	**Mass [kg]**
EPPS	156
Solar array	605
Power	126.3
Thermal control	152.2
TT & C	11.9
Command and Data Handling	31.5
Structure and Mechanisms	232.1
Total (w/o margin)	**1,315**
System Margin	**20 %**
Total (w margin)	**1,578**

Table 9: System mass budget of the space tug (Kochler, IRS)

Kochler`s approach is to not use the AVUM+ before the Moon. Instead, the space tug uses its own electric propulsion to raise its orbit, including the AVUM+, after separation from the Vega`s third stage Z9. This approach would require changes of the normal Vega launch procedure and might not be feasible without changes to the AVUM+, but it uses the same concept as the *e.deorbit* mission and the upcoming European *Space Rider*[190]*,* and offers some unique opportunities.

To raise its orbit to the desired GTO with its own electric propulsion system, the space tug would burn 150 kg of Xenon gas over a period of 185 days. In GTO, it would connect with the Ariane 5 upper stage and begins the second part of the mission, the transfer to the Moon. Instead of the so called "*weak stability boundary transfer*" (WSB), Kochler calculated a transfer like the *SMART-1* probe. This happened due to the high mass of the space tug – upper stage combination, for which there is no WSB proven mission so far. In total, Kochler calculated a delta-v of 2,545 m/s, which requires 525 kg Xenon over a period of 418 days. For the lunar capture and orbit circulation, another 87 kg Xenon and 70 days were calculated.

For the lunar impact, the electric propulsion is used until a circular orbit with an altitude of about 15 km is reached. To land the space tug with the upper stage in the target area, the AVUM+ is used. The AVUM+'s *Lunar Impact Burn* (LIB) slows the stack down by 339 m/s, resulting in an impact velocity of 1,332 m/s with a shallow impact angle. Compared to designated landers, which have a typical thrust-to-mass ratio of about 3 N/kg, the thrust-to-mass ratio of the discussed stack is about 0.36 N/kg. The resulting shape of the impact crater will be like the *SMART-1* impact. Due to the great uncertainties regarding the disruption behaviour, it can only be said with certainty that the upper stage and the space tug will disintegrate, but not exactly how.

Table 10 summarizes the delta-v budget for the mission from launcher injection to impact on the lunar surface.

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[190] Space Rider, Europe's reusable space transport system - ESA

ΔV	Size [m/s]	Propellant [kg]	Calculated TOF [days]
Orbit raising to GTO	2,608	148	185
GTO to lunar vicinity	2,800	524	418
Lunar orbit circularisation	485	87	70
Lunar impact burn	339	740 (NTO/UDMH)	16 min.
Total ST (w/o LIB)	**5,893**	**759**	**673**

Table 10: Delta-v and propellant mass budget incl. margins (Kochler, IRS)

During the mission, the space tug would use 759 kg of propellant to generate a total of delta-v of 5,893 m/s. The launch mass of the space tug of 2,337 kg results in a low injection orbit of 250 to 500 km, as the Vega--C upper stage is not used during the launch. The calculated theoretical *Time of Flight* (TOF) computes to 673 days. It is to be expected that the mission will last much longer in real life: non-thrusting phases, rendezvous alignment and the degradation of the thrust-level will prolong the TOF to two years.

In summary, the space tug on a Vega-C seems to be a theoretically feasible project. The case study by Kochler from the IRS in Stuttgart highlighted the main challenges of this project, namely the low thrust level and thus enormous transfer time as well as the high-power requirement, which leads to a weight of 2,400 kg.

A theoretical alternative to this Vega mission concept would be a direct launch of the space tug in GTO on a Soyuz launcher. The Soyuz launcher has a performance of 3,250 kg in GTO,[191] which would be sufficient for the space tug concept mentioned above.[192] The described mission time could be shortened by the 185 days for the LEO-to-GTO ascent of the space tug.

In a second optimization, the Soyuz` upper stage *Fregat* could replace the AVUM+ stage of the mission concept. The *Fregat* can be restarted up to 7 times with a total burn time of up to 1,100 sec and an Isp of 332s, compared to up to 5 restarts with a total burn time of 924 sec and an Isp of 316s in the Vega-C AVUM+ stage. To keep the rest of the concept the same, the space tug would now be added to the Fregat stage and the AVUM+ would not be used at all. This reduces the Soyuz payload mass from 3,250 kg down to 2,190 kg and the remaining propulsion of the Fregat stage could be used for the final burn on the Moon, like in the AVUM+ scenario. The transfer to the Moon would remain the same with a high ToF of 500 days.

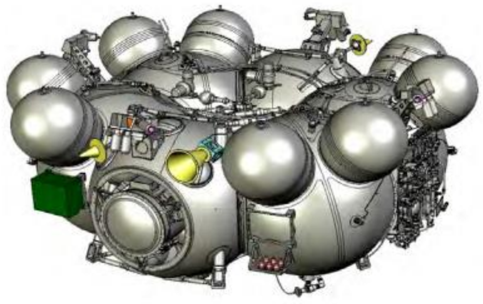

Figure 33: Soyuz Fregat upper stage (Arianespace)

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[191] Soyuz User`s Manual Issue 2 Revision 0 - Arianespace

[192] The space tug weight would be reduced by the fuel for the orbit raise into GTO of 148 kg, while the wet mass of the AVUM+ would be added.

AGORA: MISSION TO ACTIVELY REMOVE ARIANE ROCKET BODIES

At the *66th International Astronautical Congress* (IAC), a European consortium led by Kumar, Gómez, Jankovic et.al. presented the paper "*AGORA: Mission to demonstrate technologies to actively remove Ariane rocket bodies*" (see 185). *AGORA* is the abbreviation for "*Active Grabbing and Orbital Removal of Ariane*", aimed at removing discarded Ariane rocket bodies (R/Bs). The following chapter is based on the AGORA paper and summarizes the key findings and proposals of Kumar, Gómez, Jankovic et.al.

The overall framework for *AGORA* is aligned with missions such as *e.deorbit.* The mission goal is to demonstrate technologies to autonomously remove an Ariane rocket body (R/B) by 2025 with an active detumbling device and a gripping mechanism within a cost cap of 200 million euro (FY2015). [193]

The paper describes the payload systems installed on the chaser spacecraft to rendezvous, detumble, grab, and de-orbit an Ariane 5 R/B. The detumbling payload is based on an eddy current solution, which is described in the chapter "*Overview of Detumbling Technologies*". The robot payload provides (semi-)autonomous capture of the R/B with a robot manipulator based on an anthropomorphic robot finger design for the capture of the target, which was briefly described in the chapter "*Overview of Gripping Technologies*".

AGORA selected an Ariane 5 EPS upper stage in GTO as the removal target to be investigated. The GTO has been identified as the main location for Ariane (ESC-A) upper stages, as described in this study. The amount of aluminium in an EPS stage compared to an ESC-A stage is much lower, which makes the EPS less attractive as a recycling target. The EPS upper stage has a dry weight of 1,200kg. However, since AGORA targeted an EPS in GTO that was still filled with propulsion and has a weight of 3 tons, this weight comes close to the weight of an ESC-A upper stage.

Figure 34: Ariane 5 ESC-A and EPS upper stage (Arianespace)

The main phases for the mission are shown in the following figure from the *AGORA* paper:

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[193] The 200 million euro are split in 100 million euro for the actual tug and 100 million euro for the launch.

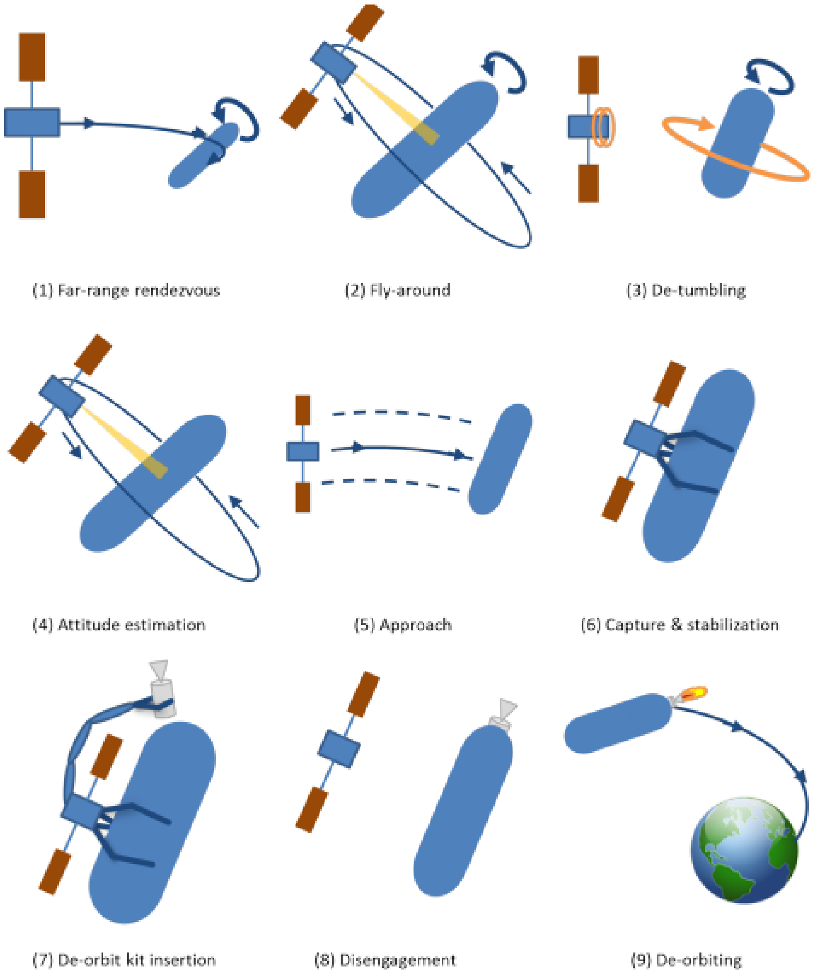

Figure 35: Schematic illustration of primary mission phases (AGORA mission concept (185))

The mission starts with a *far-range rendezvous phase*, in which the chaser reduces the relative distance to the target of kilometres to a few hundred meters. This is followed by a *fly-around manoeuvre* for visual inspection of the target. Third, the *detumbling of the target* starts via an eddy current based solution, followed by an *attitude estimation phase* to verify that the tumbling motion around all three axes meets the specified threshold. Next, the *target approach* begins, which leads to the *capturing and stabilization* of the target via the rigid clamping mechanism. In the 7th step, a dedicated *deorbit kit is inserted* into the target and the *disengagement phase* begins. In the end, the *deorbiting of the target* is ignited.

Step 1 to 6 of the *AGORA* mission could be reused directly for the planned upper stage recycling mission. Only the deorbiting kit would not be used. Instead, the upper stage is tugged further on to the Moon for recycling.

The *AGORA* chaser is based on the bus structure of ESA's *Automated Transfer Vehicle* (ATV)[194] with a total wet mass of 1,815 kg. It is equipped with:

- a de-tumbling device that will be employed to reduce the tumbling rate of the target R/B,
- a semi-rigid clamping mechanism to grab the target and compensate for any residual relative motion,
- a robotic arm to deploy the de-orbiting kit.

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[194] ATV - ESA

The main characteristics of the baseline concept are:

- total dry mass of 1,452 kg, including 20 % margin and without considering the launcher adapter mass of 150 kg,
- maximum average power consumption of 718 W and
- fully deployed configuration dimensions of the chaser of 6.89 m(L) × 17.38m (W) × 3.37m (H). The launch configuration is expected to have the following dimensions 5.32(L) × 4m (W) × 3.37m (H)).

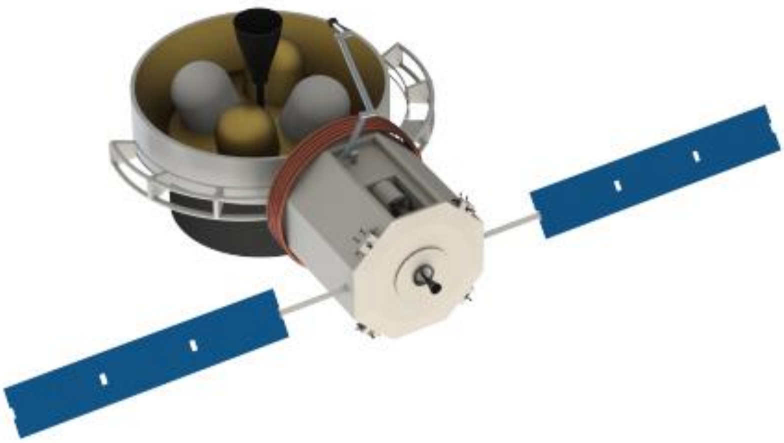

Figure 36: AGORA chaser spacecraft concept connected with EPS stage (AGORA mission concept (185))

The main subsystems are defined in what follows:

- Payload: A semi-rigid clamping mechanism composed of two finger-like tentacles, a robotic arm and an active detumbling device based on eddy currents.
- Bus: An octagonal structure made of two top and bottom panels, eight side panels and internal elements (e.g., corner brackets, fasteners, and stiffeners, etc., like what was defined in the *e.deorbit* study.
- *Attitude and Orbit Control System* (AOCS): One main, 400 N, bi-propellant Orbital Control Thruster (OCT), 24 ON/OFF bi-propellant *attitude control thrusters* (ACT) (22 N each), four *Control Moment Gyros* (CMGs), two near-field cameras, two 3D Flash LIDAR systems, two far-field infrared cameras, two Sun sensors, three star-trackers, three IMUs and two GPS receivers.
- Power: Two independent, sun-tracking solar array (SA) wings, each composed of three ATV panels, 2.1m² each, for a total area of 6.3m² per wing and two strings of Li-Ion rechargeable 30 Ah batteries. Existing ATV panels were chosen to minimize the cost of the whole mission, given that they have been successfully deployed and used in space.
- Telecommunication: three omni-directional X-band antennas for direct connection with ground stations and three TDRS S-band antennae.

The main technical budgets are:

- Mass: 276 kg for the structure, 88 kg for the thermal control subsystem, 20 kg for the mechanisms, 16 kg for the communications subsystem, 18 kg for the data handling subsystem, 137 kg for the GNC/AOCS, 93 kg for the propulsion subsystem, 97 kg for the power subsystem, 3,683 kg for the payload and 96 kg for the harness.
- Power: The power requirements are driven by the payload and the GNC/AOCS requirements. The maximum average power consumption is 718 W and maximum peak power consumption is 759 W. The calculated requested power from the SAs to power the entire spacecraft during an orbit is 1,568 W,

while the available power is estimated to be 1,703 W (851 W per wing, *End-Of-Life* (EOL), solar-pointing mode). During the mission, the power output per SA wing can vary from 250 W to 851 W per wing.

- Propellant: The propellant required for the mission was assumed to be equal to the 25 % of the chaser dry mass, thus equal to 363 kg. However, this is only a preliminary estimate.
- Cost: The cost cap for the concept was set to 200 million euro (FY2015), out of which 100 million euro are allocated for the launch.

The coil used for the detumbling subsystem is fixed to the chaser, considering the maximum radius allowed by the fairing of the Ariane SYLDA launcher. The nominal design for the coil will have a radius of 1.65 meters and 500 turns. For the coil, a standard *high temperature superconducting wire of second generation* (HTS 2G) was selected. The total mass of the required wiring is 18.5 kg. The coil operates at 65 K, and the current intensity of the coil is primed as 115 Amperes, which is below the critical intensity at this temperature.

The magnetic tensor of the target object is based on the four aluminium propellant tanks, as they contain most metallic materials within the structure. The tanks were modelled as spherical shells: 1,410 mm in diameter and 4 mm thickness made of Al7020, a typical aluminium alloy used for cryogenic propellant tanks in space. The total percentage of conductive mass over the total mass of the target is 8.8 %. Due to the non-uniformity of the field generated by the coil, a loss of efficiency of 5 % was considered.

The mean characteristic time of decay of angular velocity was determined by averaging the principal inertias of the target. This parameter indicates the exponential decay rate of the angular velocity of the target and was evaluated by the *AGORA* consortium for different relative distances between the coil and the COG of the target.

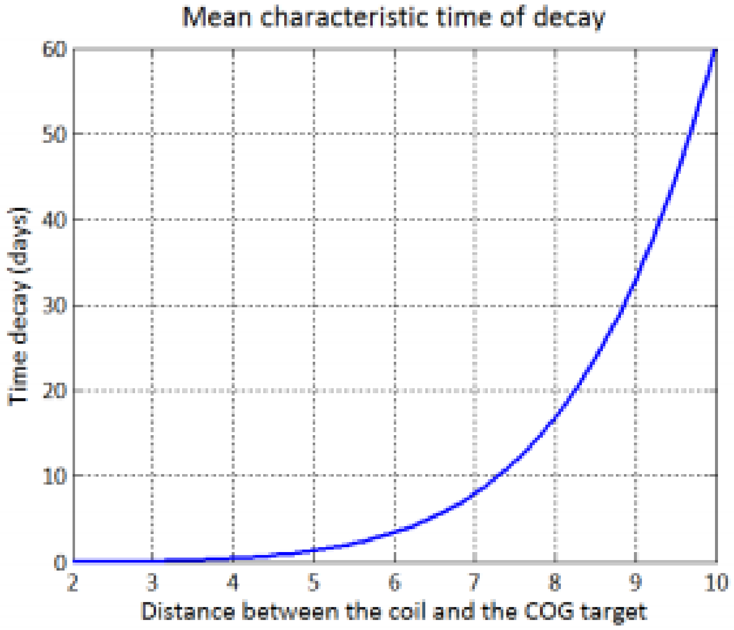

Figure 37: Mean time of decay of the angular velocity of the target (AGORA mission concept (185))

As a conclusion of *AGORA* and to ensure that the detumbling system can be used for this purpose, further studies should be devoted to the complete characterization and optimization of the design of the coil, as already proposed in the above chapter "*Overview of Detumbling Technologies*".

GNC and AOCS are also identified as key drivers for the overall concept. The GNC system must provide the required accuracy and precision and ensure that close-proximity operations are safe and the approach path is passively safe, such that anomalies do not increase the risk of collision. In addition, in view of the short reaction times, it is important that the chaser is fully autonomous during the close-range phases. In Europe, the *ClearSpace-1* mission requires similar technology and will develop missing elements in the coming years. However, it should be confirmed that this solution could be scaled to the recycling space tug and the larger target of the recycling mission discussed in this study. In addition, rendezvous and close-proximity operations in an elliptical orbit pose an additional challenge. Simulations are necessary to provide insights into the optimal guidance path, the required sensor suite, and the necessary control effort to maintain and release the relative position and velocity with respect to the target.

CONCLUSION RECYCLING SPACE TUG CONCEPTS

Two different recycling space tug concepts were analysed: the first concept is based on the Vega(-C) launcher, the second is based on a direct launch in GTO on an Ariane launcher. While the Vega is financially attractive, the total derived mission duration exceeds any realistic value. Only for LEO-based targets, the Vega would be the launcher of choice. For higher orbits, a direct launch into the target orbit (such as GTO) is required to keep the overall mission duration at an acceptable level. This requires the usage of a larger launcher such as the Soyuz or the upcoming Ariane 6x, combined with higher launch costs.

The most important components for the space tug will be precise GNC and AOCS. Solutions exists worldwide, as the *MEV-1* and *-2* missions show. These components will also be needed for the upcoming *ClearSpace-1* mission, too, where they will be validated for their effectiveness for ADR missions over the next few years.

A space-proven detumbling solution is still missing. For large, rapidly rotating targets such as uncontrolled upper stages, contactless solutions could be a viable alternative to rigid manipulators. The frequently researched eddy current method should be studied more closely to find the best coil design and materials.

The currently planned Moon transfer solely with e-propulsion leads to a long mission duration. Optimized trajectories could shorten the time required.[195] More powerful propulsion alternatives could achieve the same, but often this goes hand in hand with a higher propulsion mass. Water-based systems such as the *Microwave Electrothermal Thrusters* (MET) from Orbit Recycling`s industrial partner Momentus[196] or the "*electrolyzer*" concept of Orbit Recycling`s research partner IRS[197] could be an interesting compromise and should be further investigated. Momentus already promises a lunar transfer time of around 6 months, which would shorten the total mission time for a recycling mission to around 320 days:

- 1 day for the launch into GTO
- 4 days for approaching the GTO target (Manthey)
- 60 days to detumble the target with eddy current (e.g., AGORA)
- 1 day to grab and connect
- 180 days for the Moon transfer (e.g., Momentus)
- 70 days for lunar orbit and crash (Kochler)

The recycling mission time could be shortened by another 60 days, if the detumbling of the target is carried out in advance during a separate detumbling mission (s. chapter "*A Detumbling Chaser Satellite*"). The Moon

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[195] Practical aspects of transfer from GTO to lunar orbit - NASA

[196] Vigoride User`s Guide V2.0 - Momentus

[197] Development of a Water Propulsion System for Small Satellites

transfer time could be further optimized, reducing the ToF by up to 10%. Finally, the lunar orbit injection and landing could be shortened by at least 20 days due to larger impact burns. This optimization would result in a realistic mission duration of about 220 days versus 320 days.

RECOMMENDED NEXT STEPS

The space tug concept is still at an early stage of development and additional research needs to be carried out. The further concept development of Orbit Recycling and its research partner IRS, Stuttgart and the TU Berlin has already begun to examine two alternatives in the course of 2021.

ESA should take all these concepts, including *e.deorbit, AGORA* and others as the base for a CDF engagement.[198] The aim of the CDF should be an open discussion between various ESA experts as well as Orbit Recycling and its research and industry partner to find the optimal balance between the contradictory (propulsion) requirements of the rapid approach to the target in GTO and the long Moon transfer.

Ideally, additional synergies with existing activities can be identified, such as the upcoming electric upper stage for the Vega-C to launch payloads into higher orbits (Venus[199]), the Space Rider propulsion technology derived from the AVUM+, upcoming lunar transfer vehicles[200] for the Lunar Gateway station supply as well as component developments in the field of GNC, AOCS or manipulators. In particular, the *ClearSpace-1* mission should be closely followed to validate that the technology components developed can be scaled for the larger and heavier recycling targets and tugs.

Figure 38: Artist's view of Orbit Recycling Space Tug (Manthey, Orbit Recycling)

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[198] Concurrent Design Facility (CDF) - ESA

[199] Vega Developments - ESA

[200] Moon Cruiser Concept - airbus

MOON LANDING AND IMPACT SCENARIO

CHAPTER SUMMARY

The landing on the lunar surface takes place at a high velocity of about 800m/s, which leads to the desired disintegration of the space tug and the upper stage. Initial research by Robert Luther and Prof. Wünnemann from the *Museum für Naturkunde* in Berlin, Germany shows a resulting impact crater with a diameter of 14m and a depth of 5m.

In recent decades, many thoughts have been spent to optimize lunar transfer. Different trajectories were calculated to reduce the required transfer energy, which goes hand in hand with a reduction in propellant mass and total "mission weight". This allowed several nations to reach lunar orbit even with small satellites.[201] But a soft landing on the lunar surface still requires reducing the lander`s "*arrival*" or "*Moon orbit*" speed from about 1,670 m/s[202] to zero. This is usually achieved with a *thrust-to-mass* ratio of 3 N/kg and requires a large amount of propellant, making this the heaviest part of a typical lunar lander.[203]

In the case of the space debris recycling mission, a soft landing of the recycling tug and the upper stage is not required. In contrast, a hard landing with a crash of the object is desired since the aluminium parts of the upper stage must be dismantled for the recycling process. It is only admired, that the impact velocity is not too high to evaporate the material. Tim Kochler of the IRS, Germany analysed this concept in his cited research (see 189) and concluded that "*up to an impact speed of 1,200 m/s, ejecta like fragmentation of aluminium was not observable and that the crashed vehicle would not melt upon impact"*. Since other effects such as the plastic deformation rupture of the structures and the soil interaction would increase the energy absorption capabilities of the vehicles, even a much higher impact velocity could be considered.

The final impact velocity of the recycling tug and the upper stage is currently unknow, as it depends on the final tug design and its propulsion technology. With high degree of certainty, the tug and the ESC-A upper stage will arrive at the Moon at a velocity of 1.6 km/s. It is expected to use a retrograde (e-)propulsion to slow down the velocity in orbit, ensuring further velocity reduction by chemical propulsion during descent. The current target velocity on impact is 800 m/s, but the actual velocity can be anywhere between 800 m/s and 1.6 km/s. The tug, which is attached to the ESC-A upper stage via a clamp around the HM7B engine nozzle, will descend in the nadir direction and first hit the Moon. With a target impact angle of 90°, the HM7b Inconel 600 nozzle is driven through the aluminium tanks and cuts them apart.

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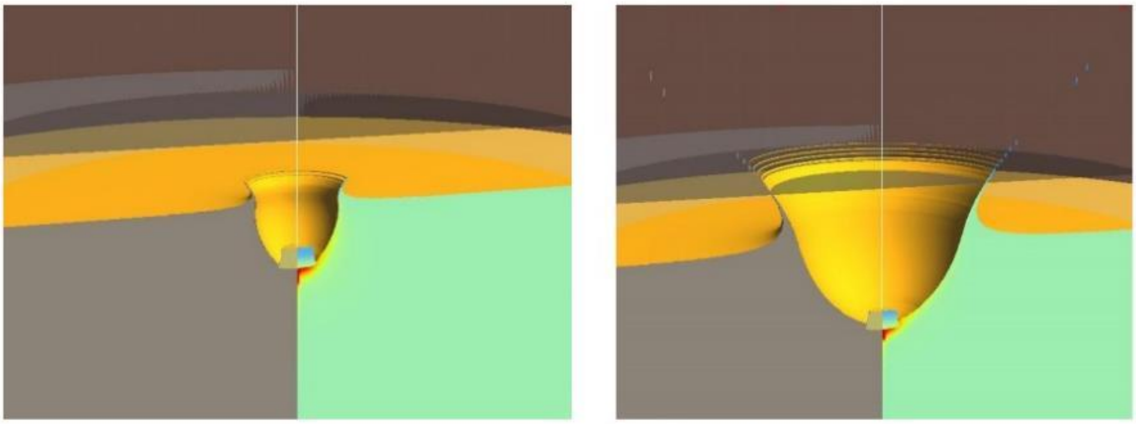
[201] List of missions to the Moon - Wikipedia

[202] The velocity depends on the orbit height and might vary accordingly.

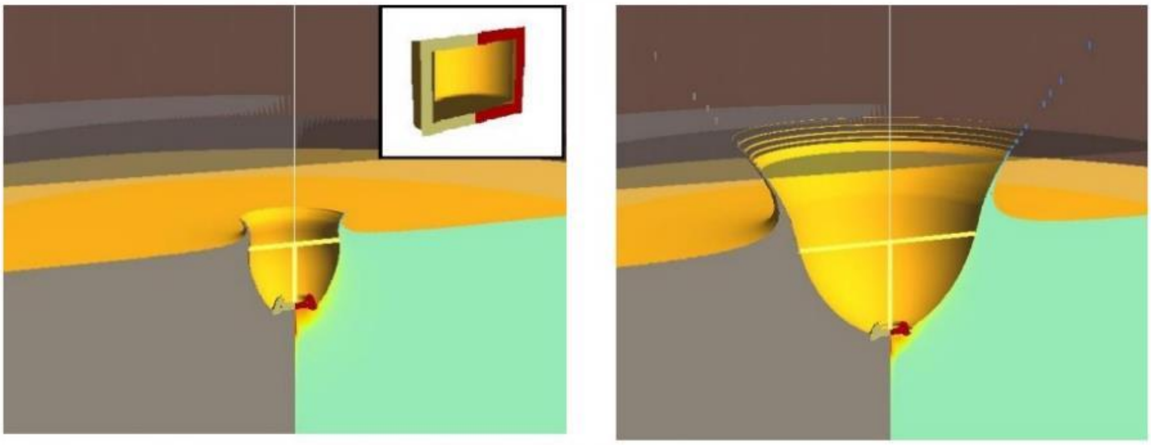
[203] The *Apollo Lunar Module* had a total mass of 15,200 kg. 8,200 kg of this were propellant for the descent.

To estimate an impact crater, Dr Robert Luther from the "*Museum für Naturkunde – Leibnitz Institut für Evolutions- und Biodiversitätsforschung*" (MFN) led by Prof. Wünnemann, Berlin, Germany simulated several impact scenarios with a velocity of 800 m/s and an impact angle of 90°. The lunar surface was simulated as regolith with 42 % porosity, 1kPA cohesion and 0.7 friction coefficient. The 2-seconds impact simulations examined 7 tonnes of aluminium projectiles that reflect the weight of the ESC-A upper stage and the weight of the space tug with margins. The projectiles were simulated from porous material and from a hollow cylinder to validate whether the projectile density would affect the expected crater formation.

The result was a crater with a diameter of around 11.1 m after 0.5 sec for the homogenous projectile and 10.8 m for the hollow cylinder. The transient crater, which evolved after 1.6 sec, reaches up to 13.8 m for the homogenous object before it may collapse. The steep crater walls expect a widening of the crater, which depends on friction angle of the regolith. The outer crater rim is said to be about 1.5 m high and initially consists out of elevated material, which is then covered with exhaust crater material.



Crater after 0,05sec (left) and 0,5sec



Crater after 0,05sec (left) and 0,5sec (right); hollow projectile as shown on top

Figure 39: Impact simulation (Luther, MfN)

The next diagram shows the evolution of the crater over the simulation time for both projectile types. The homogenous projectile is represented by the solid lines, the hollow object by the dotted lines.

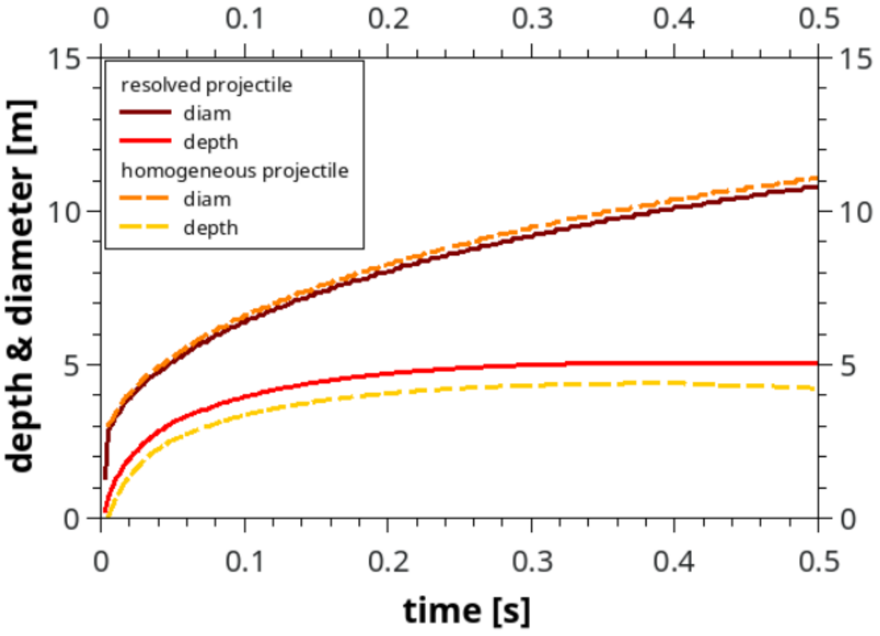


Figure 40: Impact crater development over time (Luther, MfN)

Finally, the deposition of the ejection masses of the two scenarios was checked and visualized in the next diagram. The thickness of the ejection mass is shown from the crater centre. The dashed line represents an estimate of the crater size (13.8 m radius with maximum crater volume; however, the subsequent crater collapse increases the crater by 20 %). Especially at the crater rim, due to the crater formation and the material movement, an additional increase to the ejection masses is to be expected. The thickness of the ejection mass layer is to be understood only as an average value, especially at a greater distance. With 3 crater radii, the ejection ceiling passes from a continuous ceiling into a loose (non-contiguous) ceiling, in which individual fragments can also be larger than the specified thickness.

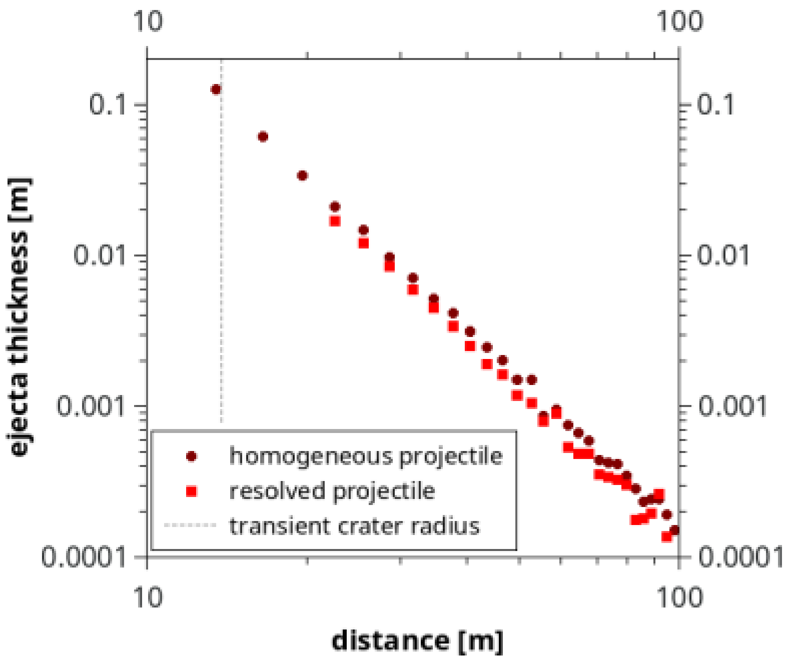


Figure 41: Impact ejecta thickness over distance (Luther, MfN)

Luther`s simulations are a first step towards better understanding the expected impact scenario, when the recycling tug and the upper stages will hit the lunar surface.

One result that is not shown in the diagrams is that the impact velocity will be a key factor in crater formation. Unfortunately, high-speed impacts are non-linear events, which means that an impact velocity of 50% does not necessarily mean a crater that is half as wide and deep.

In addition, the impact angle is another variable that must be considered: a shallow impact will distribute the recycling tug and upper stage material differently than a steep impact. The observed Moon impacts of *LCROSS*, *SMART-1* and the *Chandrayaan 2 Vikram* lander prove this claim. Finding the ideal impact velocity and angle remains an important optimization challenge for the recycling mission, which must be solved in future research.

RECOMMENDED NEXT STEPS

To better understand the crater dependencies of impact velocity and impact angle, additional experiments should be carried out. The MfN in Berlin, Germany around the renowned research group of Prof. Wünnemann as well as the Fraunhofer EMI Institute, Freiburg, Germany are both ideally suited for such research and are described with their skills in the appendix. Since a good understanding of the expected impact behaviour is relevant for all future lunar missions, the following complementary research activity is proposed:

The complex impact processes can be simulated with advanced hydrocodes with large-scale models of the upper stage. These numerical simulations are complemented by impact experiments used for validation. In a first phase, simple, scaled simulations of the impact scenario can demonstrate the key features of the “soft landing”. This includes:

- Performance of a dedicated experiment using a two-stage light gas gun. A hollow aluminium cylinder (e.g., 6 mm diameter) serves as an upper stage equivalent to be impacted on sandstone target at a given speed. High-speed video of the impact processes and fragment collection after experiment are used for experiment evaluation.
- Numerical simulation of the experiment using the sophisticated SPH hydrocode SOPHIA and specific material models to characterize the fragmentation behaviour of the simulant upper stage and track its fragments.
- Numerical simulations of the impact scenario using the iSALE shock physics code allow to further investigate the crater evolution and material ejection taking into account different impact velocities, projectile masses and target properties.

These simulations are intended to provide insights into the complex impact processes and show the concept on a small scale. Furthermore, the simulation approach is demonstrated, which can be used to scientifically evaluate the upper stage impacts in dependence of impact and design parameters for a representative upper stage model at a large scale. The experimental and numerical simulation of impacts on the lunar surface contributes directly to the verification of the Orbit Recycling concept by asking fundamental questions such as:

- What is the crater size?
- How does the upper stage disintegrate during impact?
- How are upper stage fragments distributed around the impact location?
  How are lunar ejecta particles ejected?

RECOVERY OF SPACE DEBRIS FRAGMENTS AFTER IMPACT

CHAPTER SUMMARY

The research on the recovery of space debris fragments after an impact on the lunar surface was carried out by Nicholas Smith from the research group led by Lennart Kryza and Prof. Brieß, TU Berlin in collaboration with Frank Koch, Orbit Recycling. The aim of this study was to determine the general feasibility of recovering debris fragments after a Moon impact. An in-depth discussion of the process yields system requirements across the launch, space, and ground segments. Mass and power budgets, cost analysis, and mission risks are discussed, the expected mission timeline is presented and next steps to reduce risks and to close knowledge gaps are proposed. Smith concludes that the costs per kilogram of aluminium would not exceed 150,000 Euro.

Some of Smith`s results are cited below. For more details reference is made to Smith's original study.[204]

FRAGMENT RECOVERY OVERVIEW

The aim of Smith`s study is to determine the feasibility of a lunar base preparation mission using recycled aluminium supplied through the Orbit Recycling debris capture and transportation process. A simplified summary of Smith`s work sees the transport of 2 small rovers to the Moon that will search, collect, and recover the fragments of the impacted upper stage / space tug combination from the impact location. The fragments are then taken to a central recycling station near to the impact side, where the actual melting and casting of the aluminium will take place.

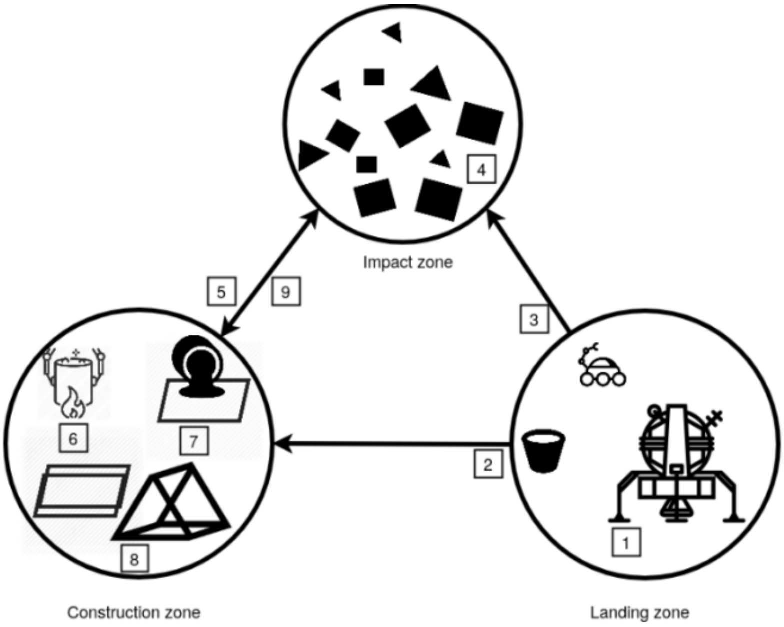


Figure 42: Aluminium recycling process on the Moon (Smith, TU Berlin)

The process steps are summarized here:

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[204] *“Feasibility Analysis and Architecture of a Lunar Base Preparation Mission Using Recycled Aluminium”*, Nicholas P. Smith, Lennart Kryza, Prof. Brieß, Master`s Thesis at TU Berlin, 2020

1. Landing of lander. Egress of rover, melting and casting mechanism from the lander.
2. Placement of the melting and casting mechanism in the construction zone.
3. Traverse of the rover from landing zone to the impact zone.
4. Collection of aluminium from impact zone.
5. Transport of aluminium to the construction zone.
6. Melting of aluminium.
7. Casting into sheets.
8. Sheet stacking according to size. If possible, construction of tent structure.
9. Repetition of steps 4-8 until aluminium supply is exhausted.

RECYCLING LOCATION

The mission has identified the *Schrödinger basin* as its reference landing site. As explained in more details in Smith`s paper, the impact of the upper stages is expected to occur within a 2.4 km diameter. Smith uses an impact scenario like Luther`s simulation above (s. "*Moon Landing and Impact Scenario*"). Even though the landing of the EL3 will occur after the impact of the ESC-A, the region defined by the 2.4 km diameter will remain as the target impact area for future impacts of recovered ESC-A bodies.

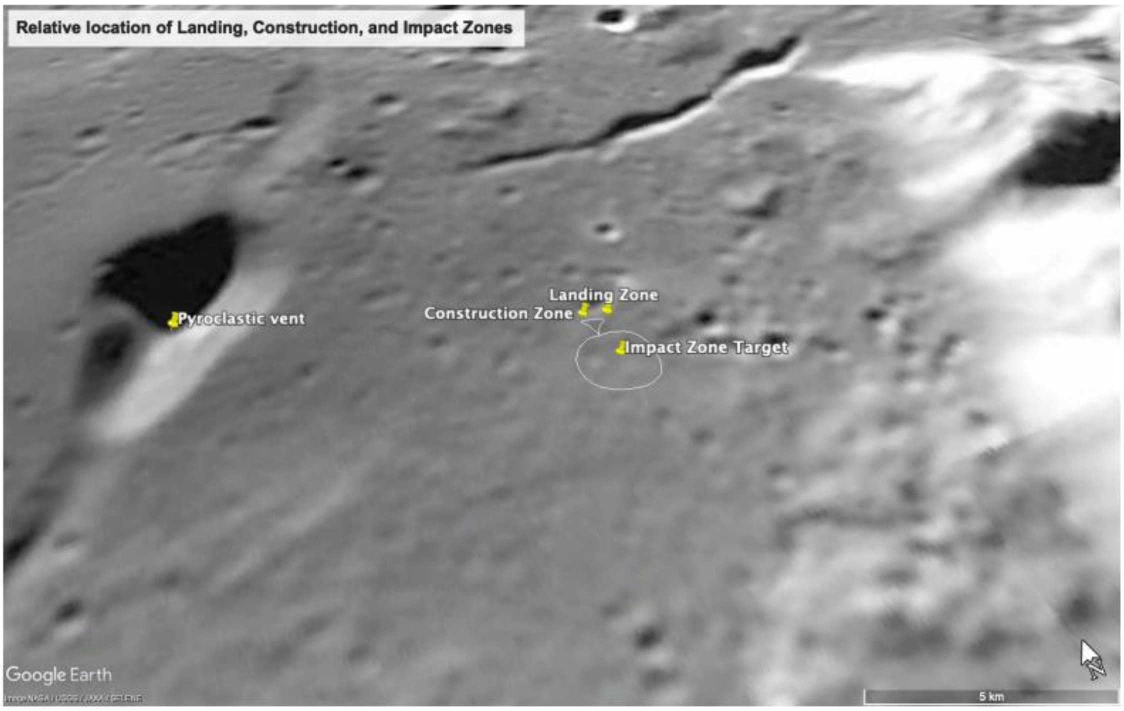

Figure 43: Relative location of Landing, Impact and Construction Zones (Smith, TU Berlin)

The expected crash diameter is 200 m, including 5 crater radii ejecta blanket plus 30 % margin to encompass the near-total ejecta blanket. A 50 % margin is added to the impact target radius plus the crash radius to locate the landing target a minimum of 2 km from the centre of the impact target and 0.7 km from the nearest possible impact zone. A depiction of the impact target and landing target relationship is given in Figure 44. The minimum distance of an aluminium location is 0.7 km and the maximum distance is 3.4 km.

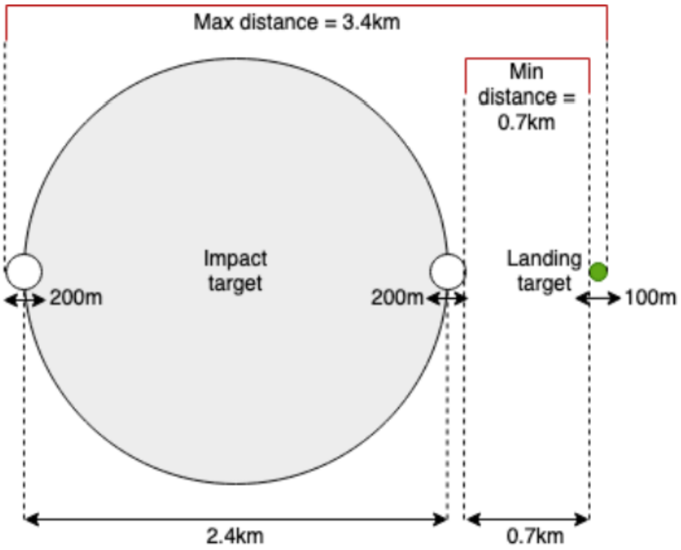

Figure 44: Impact target and landing target zone location scenarios (Smith, TU Berlin)

RECYCLING INFRASTRUCTURE COMPONENTS

To minimize development time and cost, an architecture was originally proposed that leverages systems from the *Human-Enhanced Robotic Architecture and Capability for Lunar Exploration and Science* (HERACLES) mission.[205] In the meantime, HERACLES was superseded by the *European Large Logistic Lander* (EL3)[206], which was reflected by Smith. The EL3 can be launched on the Ariane 64 and offers a payload to the Moon of 1,500 kg.

Figure 45: European Large Logistics Lander EL3 (ESA)

For the rover, Smith proposes to use the *Precursor to Human and Scientific Rover* (PHASR)[207], which was planned for the HERACLES mission. PHASR is developed by the Canadian Space Agency CSA, has a weight of about 390 kg and can travel up to 2,000 km during its lifespan.

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[205] Heracles lander and rover - ESA
[206] European Large Logistics Lander - ESA
[207] PHASR - CSA

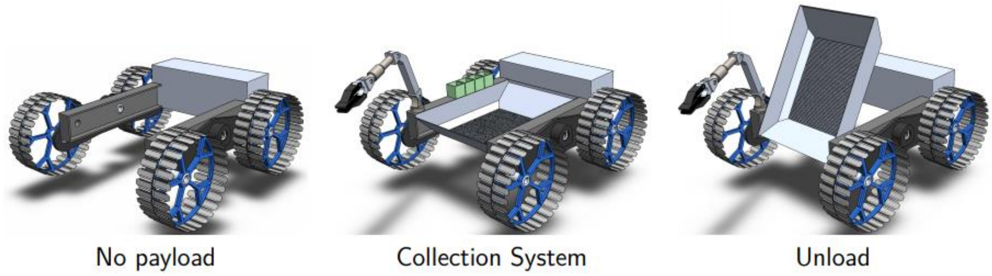

Figure 46: Aluminium collection subsystem concept (Smith, TU Berlin)

Multiple systems may be launched over an extended period, but the first launch should provide systems necessary to process at least one Ariane ESC-A body. Finally, the system must be so cost effective such that the total cost per kilogram of processed aluminium does not exceed that of alternate or traditional methods of structural material transport. The results of Smith`s analysis confirm the feasibility of completing the mission with the architecture shown in Table 11, at a cost anticipated to be competitive with current and in-development technologies while recovering 40 % of the available aluminium.

Launch	Launch Vehicle	Ariane 6 A64
Space	Lander	EL3 "Cargo Delivery"
	Collection	PHASR-Light + Collection payload
	Melting/Casting	PHASR-Light + Melting/Casting payload
Ground	Network	LOP-G + ESTRACK
	Operations	ESA/ESOC

Table 11: Mission Architecture (Smith, TU Berlin)

Due to the presence of two PHASR rovers that Smith proposed for his study, the *HERACLES* (“*Science Mission*”) configuration of EL3 cannot be used. The "*Cargo Delivery*" configuration of EL3 provides sufficient payload volume and mass to deliver the complete architecture in a single launch. Further, a key advantage of integration with PHASR, beyond development schedule and cost efficiencies, is flexibility of payload configuration, especially if an *Artemis Jr*-like chassis can be assumed. PHASR can function for both collection and transportation as well as melting and casting functions by configuring appropriate payloads onto separate chassis. However, the mass and power budgets used in Smith`s work to estimate the mission timeline in Table 12 show the challenge of meeting the PHASR-Light volume and mass requirements.

	Continuous operation			Battery charge		
Milestone	Min	Mean	Max	Min	Mean	Max
1x1*m* sheet	1	1	1	1	1	1
Two 3x3*m* sheets	1	2	3	2	5	9
40% collected	2	5	8	7	16	31

Table 12: Lunar day of milestone completion (Smith, TU Berlin)

The mass and power budgets are based on many assumptions and are not expected to represent the final system closely. However, the integration with PHASR assumes that mass and power requirements are met. PHASR-Light provides at least 90*kg* for payload, which is sufficient for the "*Collection PHASR*". The "*Melting and Casting PHASR"* may require up to 150*kg* payload capacity, still within the bounds of possible PHASR configurations.

Concepts for the detection, collection, transportation, melting, and casting payloads were discussed in Smith`s study. Detection utilizes an IR camera for surface-level operations. With the planned PHASR *ground penetrating RADAR* (GPR), sub-surface operations may be possible, or a metal detector may be required. In autumn 2020, Stephan Linke, TU Braunschweig / TU Berlin, conducted a test campaign with an experimental rover, which was equipped with a device for metal detection based on the induction method. The rover drove autonomously through the test site and was able to detect numerous metal objects and mark them on a digital map.[208] Work at TU Berlin will continue in the coming months together with Orbit Recycling.

Based on available data, it is possible to capture the impact fragments with the planned PHASR manipulator arm. An additional end effector is included in the suite - an electric shear – to reduce the size of aluminium fragments. Depending on final payload availability, a second manipulator arm may be included, which provides operational advantages in gripping, cutting, and digging. Orbit Recycling is in close contact with *Made in Space Europe – a Redwire company*, that provides a manipulator for the PHASR concept under discussion.

The aluminium is transported via a tiltable storage basin, as Smith shows in his study. The actual melting and casting concept for a 1x1x0.005*m* sheet has been proposed with extendibility to larger sheet sizes and is discussed in more details in a separate chapter below (s. "*Aluminium Casting in Regolith*").

Figure 47 shows the activity of the two rovers during the first two lunar days. An average activity duration is assumed. The first timeline assumes continuous operations. The second includes predicted charging intervals for batteries. The charging time of an induction furnace battery is not included, as Fresnel lenses can be used instead.

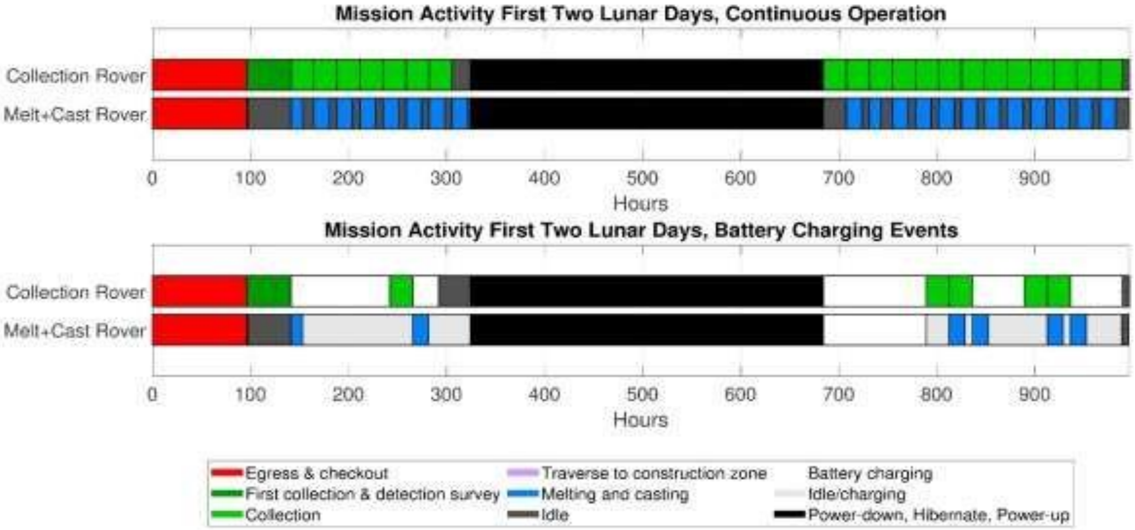

Figure 47: Collection and melting/casting rover activity timelines (Smith, TU Berlin)

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[208] More information is available in the appendix at "*Introduction TU Braunschweig / TU Berlin*".

RECYCLING RECOVERY RATE

Smith discusses two scenarios with an estimated rover and melting infrastructure lifespan of 2 or 5 years. In each of the two scenarios, a certain minimum number of ESC-A bodies must be recovered to achieve the desired level of cost efficiency. 42 ESC-A bodies in the 40 % recovery rate / 5-year system life scenario and 49 ESC-A bodies in the 60 % recovery rate / 2-year system life scenario is required to be recovered before subsequent launches and hardware (ESC-A recovery tugs, lunar Al processing systems) no longer raise the cost per kilogram above that of direct aluminium transport. This cost is expected to be about 150,000 Euro per kilogram of aluminium. This is shown in Figure 48and Figure 49.[209]

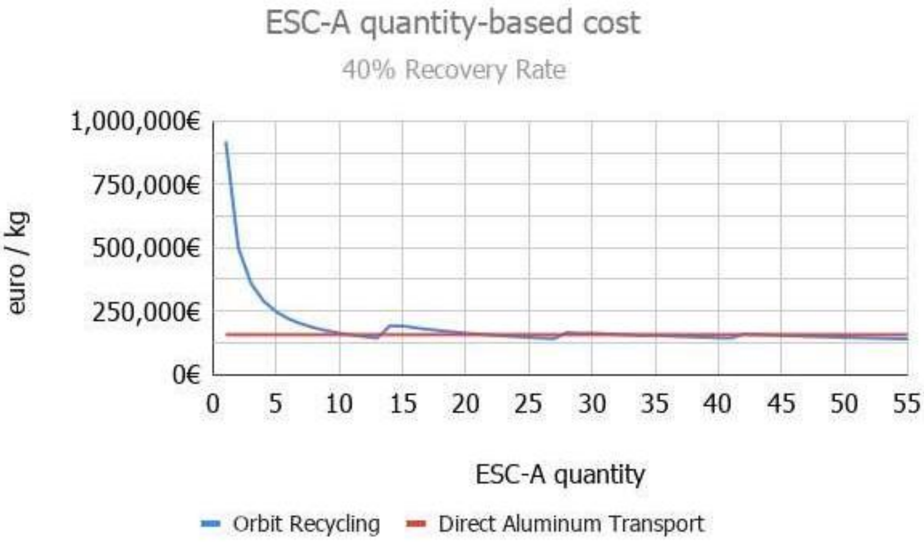

Figure 48: Orbit Recycling cost per kilogram per ESC-A, 40% recovery rate (Smith, TU Berlin)

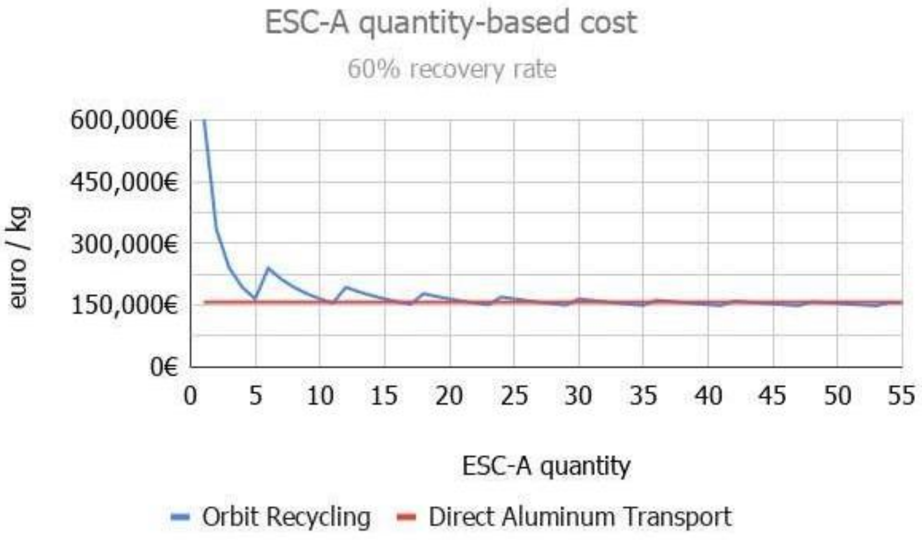

Figure 49: Orbit Recycling cost per kilogram per ESC-A, 60% recovery rate. (Smith, TU Berlin)

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[209] The complete initial set of constraints identified for this mission are listed in Table 2.3. of the cited study of Nicholas P. Smith, TU Berlin

The "breakeven" point for the recycling scenarios compared to direct aluminium transport is shown in Figure 50 and Figure 51. The final user requirements set conditions on the quantity and structure of the completed aluminium processing. The 150,000 euro per kilogram of aluminium for the direct transport costs are an assumption, driven by Orbit Recycling`s goal of not exceeding this price for the recycled aluminium.

Figure 50: Orbit Recycling vs. direct Al transport cost per kg, 5-year system life (Smith, TU Berlin)

Figure 51: Orbit Recycling vs. direct Al transport cost per kg, 2-year system life (Smith, TU Berlin)

RECOMMENDED NEXT STEPS

Smith analysis describes an early-stage concept for the successful recovery of aluminium fragments from an impacted Ariane upper stage on the Moon for recycling. Soon, specific next steps can be taken to further define the architecture and reduce project risk. These steps are directly tied to the risks identified throughout Smith`s work. Recommended actions to address the highest risk items which are independent from the HERACLES / EL3 mission architecture are:

- Simulation and study of impact crater characteristics and aluminium wreckage distribution and fragment size as described in more details in the chapter “*Moon Landing and Impact Scenario*”.
- Architecture and process design for lunar Fresnel lens-based melting and casting as described in a chapter “*Regolith Sintering with Concentrated Sunlight*”.
- Force and coefficient of friction analysis and testing for lifting, gripping, and excavating aluminium fragments of diverse sizes and depths.
- Environmental aluminium detection testing and simulation using IR camera for on surface detection and GPR and metal detector for sub-surface detection.
- In-situ aluminium cutting method design and testing. Viability study for integration as manipulator arm end effector.
- Development and testing of navigation mapping system for wide-area aluminium identification survey.
- Detailed *digital elevation maps*-based traverse and path planning analysis for the target traverses.

Smith and Koch propose a concept that depends heavily on data from systems that are themselves in Phase A. In the development of the concept, several trades were considered, including

- integration with HERACLES / EL3 using a single PHASR-Light system vs. EL3 "Cargo Delivery" using multiple PHASR systems,
- required excavation depth, excavation method, excavation time of the simulated lunar impact,
- use of an induction furnace vs. Fresnel lenses for melting, and
- inclusion of a second manipulator arm on the PHASR rover.

These trades should be re-examined at a time when more information on the Ariane 6 A64, EL3, and PHASR is available. The result of this reassessment based on redefined system specifications should lead to a further iteration of the concept.

In addition, an architecture should be investigated that is not bound to the EL3 and PHASR. A CDF is proposed like the space tug situation (p. 73), where experts from ESA, Orbit Recycling and the European space industry should evaluate synergies with other relevant developments around (lunar) rover, manipulators, gripping mechanism, location-based services on the Moon, and others.

ALUMINIUM CASTING IN REGOLITH

CHAPTER SUMMARY

The concept of Orbit Recycling is to use recycled aluminium on the Moon as construction material. This includes the melting and casting of the aluminium, which not only allows the creation of large or fragile objects but also negates any space aging effects of the source material, since it is completely melted during the process.

Earth-based manufacturing relies on sand-casting or permanent mould casting processes. Experiments were carried out by Julian Baasch, Lea-Jean Böshans, Stefan Linke, Prof. Stoll from TU Braunschweig / TU Berlin and Frank Koch, Orbit Recycling with aluminium, Al-alloys, and regolith simulant to prove that it is possible to cast a wide range of aluminium parts with lunar regolith as a mould. The results show that casting aluminium on the Moon should be "*feasible with today`s technology*".

Space agencies, space industry as well as architects around the word are working on the concept of a permanent human presence on the Moon.[210] Various habitation modules were proposed, varying in purpose, type, and technology.[211] They all have certain components made of aluminium in common, either for wall segments, airlocks, structures that hold solar panels for the energy supply and much more.

In the CDF study repot *CDF-202(a) Issue, 1.1,*[212] a conceptual design of a lunar habitat study was performed in the ESTEC Concurrent Design Facility (CDF) by *Skidmore, Owings & Merrill* (SOM), in collaboration with ESA and the *Department of Aeronautics and Astronautics of the Massachusetts Institute of Technology* (MIT). Although several core components of this concept would be brought from Earth to the Moon, certain elements, especially in the energy supply sector such as the towers for solar panels could still be built locally on the Moon. This space manufacturing, or better *Moon manufacturing*, could be supplied by recycled aluminium from derelict upper stages.

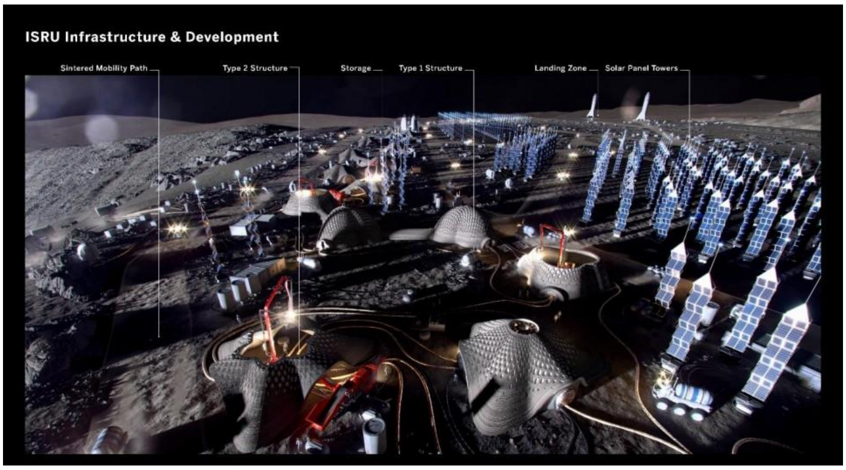

Figure 52: "Moon Village" (Skidmore, Owings & Merrill, (212))

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[210] Global Exploration Roadmap Supplement – Lunar Surface Exploration Scenario Update

[211] E.g., Moon Camp Challenge 2020-2021 - ESA

[212] ESA engineers assess Moon Village habitat - ESA

On Earth, various process technologies are used to create new objects made of aluminium. *Rolling* or *bending* could be used with sheet metal,[213] while *additive manufacturing* (AM) would be an option for aluminium powder.[214] Sand-casting or permanent mould casting is a third option,[215] that allows the manufacturing of all types of objects, from small to large and from individual shapes to (small) series of equivalent items. Compared to AM, the casting material has fewer requirements for purity and preparation. All it takes is to heat the aluminium (including potential contaminations) to about 660°C to liquefy it. As shown in chapter "*Regolith Sintering with Concentrated Sunlight*", this could even be done with concentrated sunlight.

Julian Baasch, Lea-Jean Böshans, Stefan Linke and Prof. Enrico Stoll of TU Braunschweig / TU Berlin and Frank Koch, Orbit Recycling conducted various experiments with aluminium which is poured into moulds from regolith simulant.[216] Instead of special green sand, lunar regolith was formed and/or sintered to produce a mould for sand-casting or permanent mould casting. The experiments investigated the interaction between cast aluminium and simulant as well as the general casting behaviour and showed that it was possible to cast a wide range of aluminium parts with lunar regolith as the moulding material.

Using sintering techniques, the mould can be further hardened. Figure 53 shows a sintered mould on the left side with the resulting cast on the right side. With these sintered moulds, it was possible to perform several castings before the mould was damaged. This approach demonstrates a new ISRU--based customized process that makes it easy to produce metal castings on the Moon from space resources.

Figure 53: (Left) Sintered regolith simulant mould and (Right) resulting aluminium casting (Baasch)

The aluminium object shown in Figure 53 is a first wall segment prototype by Baasch for a lunar habitat concept, developed by Frank Koch, Orbit Recycling. Over time, the production quality of the segments was further improved by Baasch and Böshans, and small series of similar segments could now be produced from a single mould that would be joined together, as shown in Figure 54 below.

Due to the simple shape of the segments, the mould on the Moon could be easily created with an automated rover, as shown in Figure 54. First, the regolith mould is generated by pushing the regolith of the lunar surface into the desired outline. Second, the mould is filled with liquefied aluminium. Third, the surface of the cast could be smoothened until the aluminium is solidified again.

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[213] Bending - Wikipedia
[214] 3D Printing - Wikipedia
[215] Casting - Wikipedia
[216] Regolith as substitute mold material for aluminium casting on the Moon

On the Moon, the solidification takes place merely by thermal radiation from the aluminium surface, which takes up to 15 minutes and leaves enough time for the post-processing of the cast. Finally, the individual wall segments are positioned and welded together. The welding of the aluminium can be done with concentrated sunlight or with classic welding technology including LASER welding.[217] The advantage of the lunar production site is that there is no atmosphere on the Moon. On Earth, the oxidation of aluminium makes welding complicated and energy demanding, while in vacuum, aluminium welding is much easier.[218]

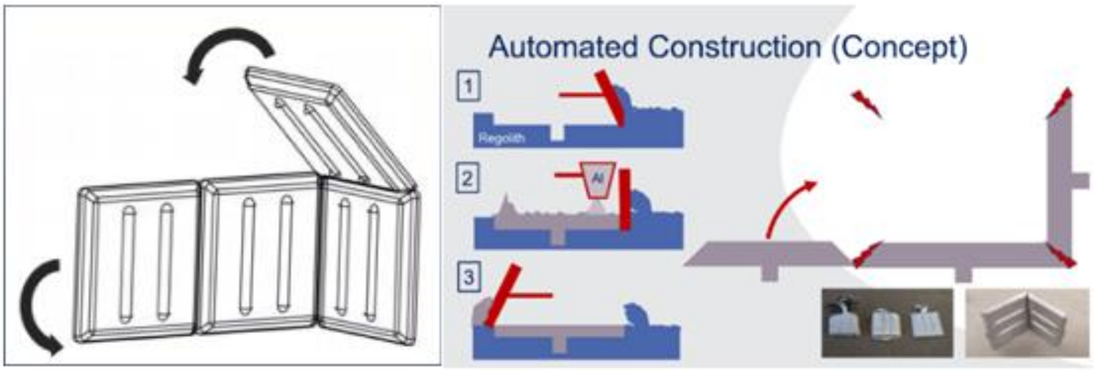
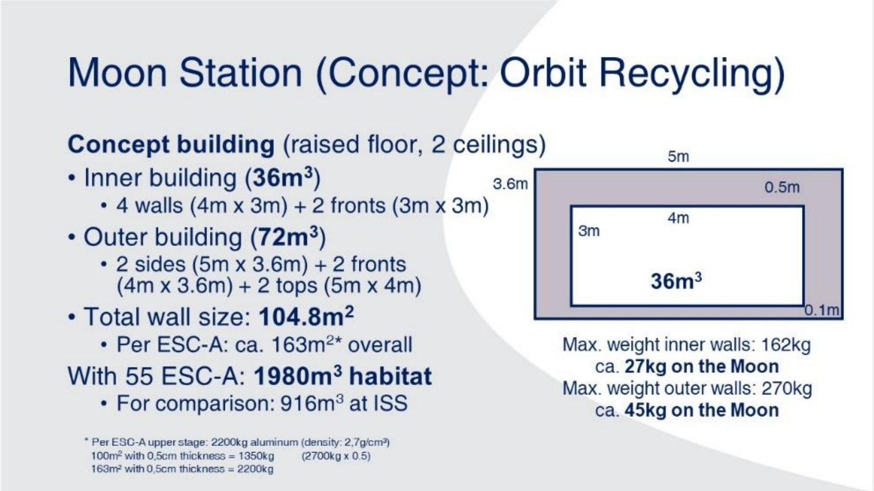


Figure 54: Automated aluminium wall segments for the Moon station (Orbit Recycling)

To demonstrate the potential of this concept, Orbit Recycling developed a habitat from recycled Ariane 5 upper stages, shown in Figure 55. With the amount of aluminium from a single Ariane 5 upper stage, a double-walled housing measuring 3m x 3m x 4m (inside walls) and 3.6m x 4m x 5m (outside walls) could be cast, resulting in a volume of 36m^3. The space between the walls could be filled with regolith for radiation protection or used for cables and tubes. Due to the reduced gravity on the Moon, the wall segments will weight much less than on Earth. The largest inner wall segment would weight 27 kg on the Moon, while the outer wall would weight about 45 kg, making handling of the segments easy: even small rover and robotic manipulators could handle these weights on the Moon. This concept of individual habitat modules, which could be constructed as needed over time, puts the vision of a *Moon Village* into reality.


Moon Station (Concept: Orbit Recycling)

Concept building (raised floor, 2 ceilings)
- Inner building (**36m^3**)
  - 4 walls (4m x 3m) + 2 fronts (3m x 3m)
- Outer building (**72m^3**)
  - 2 sides (5m x 3.6m) + 2 fronts (4m x 3.6m) + 2 tops (5m x 4m)
- Total wall size: **104.8m^2**
  - Per ESC-A: ca. 163m^{2*} overall

With 55 ESC-A: **1980m^3 habitat**
- For comparison: 916m^3 at ISS

* Per ESC-A upper stage: 2200kg aluminum (density: 2,7g/cm^3)
100m^2 with 0,5cm thickness = 1350kg (2700kg x 0.5)
163m^2 with 0,5cm thickness = 2200kg

Max. weight inner walls: 162kg
ca. **27kg on the Moon**
Max. weight outer walls: 270kg
ca. **45kg on the Moon**

Figure 55 Aluminium Moon habitat concept (Orbit Recycling)

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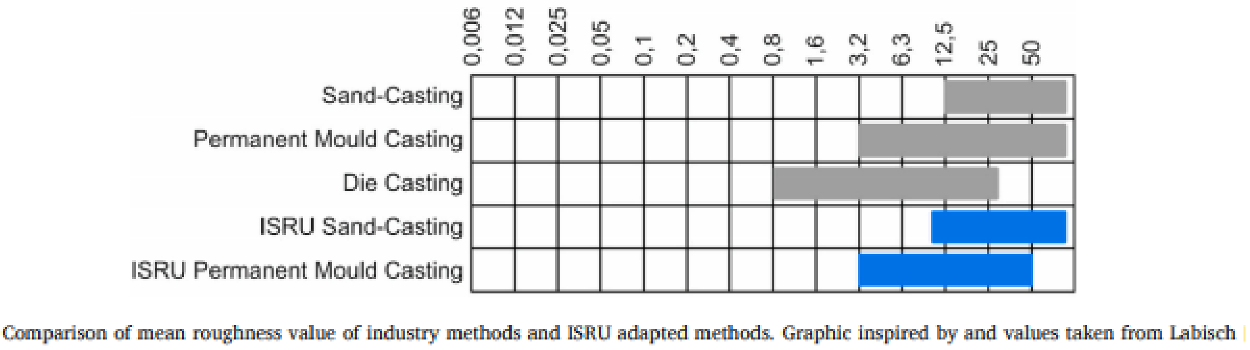
[217] Aluminium Alloy LASER Welding - machinemfg.com
[218] LASER Welding under Vacuum: A Review

However, aluminium casting is not limited to large wall segments. At ESA`s *European Astronauts Centre* (EAC) near Cologne, Germany, Lukas Schlüter (now DLR) manufactured tools made of aluminium in the *EAC-1*regolith simulant. The experiments were carried out in collaboration with Frank Koch, Orbit Recycling and show the potential to cast smaller objects on the Moon: If a tool breaks, astronauts would not have to wait for hours for a replacement tools to be produced by AM, or to wait weeks and months for the next delivery from Earth. Instead, the broken tool could be pressed into the surface of the Moon and aluminium probes would be heated in a matter of minutes to cast a replica. Even with the cleaning of the cast of rough edges and moulding material, this process would be the fastest supply alternative on the Moon.

Figure 56 Tools cast out of aluminium by Lukas Schlüter (image: Orbit Recycling)

To understand the achievable casting quality of the straightforward process described above, Böshans from TU Braunschweig investigated further aspects of the regolith casting process.[219] First, the mean roughness value of different methods was determined. Baasch and Böshans showed that the regolith sand casting and the regolith permanent mould casting achieve comparable results to conventional casting processes on Earth.



Comparison of mean roughness value of industry methods and ISRU adapted methods. Graphic inspired by and values taken from Labisch

Figure 57: Mean roughness value of casting methods (Baasch, Böshans, TU Braunschweig)

In addition, Böshans took a closer look at the mould shrinkage effect that occurs during the sintering process. Böshans concluded that the particle size of the regolith used for the mould and the mould sinter temperature have an impact on the achievable casting quality as well as on the achievable number of castings per mould, as summarized in Table 13.

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[219] “*Untersuchungen von Kokillengussformen aus Regolithsimulant für den Aluminiumguss*”, Lea-Jean Böshans, Institut für Raumfahrtsysteme, TU Braunschweig, Germany (unpublished, German)

Particle size [µm] Sinter temperature	0-45 1000°C	0-45 1025°C	0-45 1050°C	45-90 1050°C
Strength	Not sufficient	Sufficient	Good	Good
Distortion of mould	Very small	Small	Significant	Significant
Shrinking	Very small	Small	Very significant	Significant
Crack formation	Small	Significant	Very significant	Small
No. of cast	0	>3	3	1

Table 13: Casting results depending on mould sintering processes (Böshans, TU Braunschweig)

Finally, Böshans carried out first tensile tests with aluminium alloys cast in regolith. The values of the tensile samples hardly differed, but due to the small sample size of Böshans, this should be viewed with caution and repeated with a larger number of test samples.

But due to the casting, the Al2219 T87 alloy experienced a severe loss of strength and elastic stiffness. Due to the low tensile strength, Böshans assumed that a coarse-grained, “*globulitic*” casting structure had formed, which leads to a sharp decrease in the achieved cast strength. Further studies of the effects of the grain structure of the mould and various “*heat treatments*” of the mould and the cast during the casting process, in particular the temperature changes over time (cooling), are needed to better understand and further improve the achievable casting quality of aluminium in regolith moulds.

CONCLUSION ALUMINIUM RECYCLING ON THE MOON

Based on the results of Baasch, Böshans, Linke and Stoll of TU Braunschweig / TU Berlin, Frank Koch, Orbit Recycling is convinced that aluminium casting in regolith is possible and that it could thus be simplified to carry out this process automatically by rovers and robotics on the Moon with minimal effort. This would allow the production of large habitats or shelter segments directly on the Moon as well as the casting of (replacement) objects on demand.

In addition to casting, the recycled aluminium could also be used for other purposes. While burning a material as fuel is not officially considered as recycling (p. 13), it is still an important and relevant use case for space. If grinded fine enough, aluminium powder could be used with oxygen as a propulsion material for spaceships. Currently, methods for obtaining oxygen from regolith are being developed. ESA is conducting numerous studies in this area,[220] while NASA contracted *Wickmann Spacecraft & Propulsion Company*, Casper, USA, to develop a lunar propellant consisting of gelled liquid oxygen and aluminium powder.[221] In addition to harvesting this aluminium on the Moon from regolith, especially at the beginning of the Moon exploration, it could be recycled from space debris with less effort.

Alternatively, the recycled aluminium could be used as a cathode material for *Neumann Thruster,*[222] which uses a “*Centre-Triggered Pulsed Cathodic Arc Thruster”* (CT-PCAT) technology to convert a solid conductive fuel rod

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[220] Turning Moon dust into oxygen - ESA
[221] Wickmanspacecraft.com
[222] Neumannspace.com

into plasma to generate thrust.[223] The system can use a range of conductive fuels including aluminium, which could easily be cast into the required rod from space debris. The use of regained aluminium from impacted upper stages as propulsion material on the Moon offers a second important use case for the debris material.

RECOMMENDED NEXT STEPS

Although the results of the first experiments by Orbit Recycling and TU Braunschweig / TU Berlin are promising, the overall knowledge about aluminium casting in regolith mould is still limited. Baasch and Böshans described several areas for process improvements that should be investigated in more details soon. As part of a joint doctorate with the EAC, Cologne, Baasch will continue research on this topic together with Orbit Recycling at the TU Berlin over the next 3 years.

In addition, aluminium smelting and casting experiments should be carried out under vacuum conditions, in particular for the aluminium alloy Al2219, which is used in the Ariane 5 upper stages. These experiments should give a better understanding of the achievable results on the Moon without the oxidation effects of the Earth`s atmosphere.

Finally, another use case for the aluminium on the Moon was identified by Orbit Recycling. By mixing aluminium (powder) with regolith, a new material composition (*ALReCo*) could be produced. Initial experiments show superior thermal conductivity and thermal capacity of this new material compared to pure regolith. Depending on the proportion of aluminium, the material can act as an electric conductor and be weld or drilled without breaking. Likewise, the tensile parameters are improved compared to regolith.

This material could even be suitable as a heat storage solution for a lunar ground station. Tests conducted under ESA contract Nr. 4000119561/17/F/MOS by *Azimut Space*, Berlin, Germany (formerly *Sonaca Space*) showed that the regolith alone has limited capabilities for such a scenario, while the new composition may be able to close the identified gaps. This should be validated in a separate research study.

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[223] Centre-Triggered Pulsed Cathodic Arc Spacecraft Propulsion Systems

REGOLITH SINTERING WITH CONCENTRATED SUNLIGHT

CHAPTER SUMMARY

To produce large moulds for aluminium casting on the Moon, various regolith sintering concepts were evaluated by Orbit Recycling. Fresnel lenses are an efficient option because they do not require an external power supply and can be operated without time limits for cooling or battery charging. In additional, Fresnel lenses could be used to glaze surfaces on the Moon to avoid dust problems, as well as for the aluminium melting itself. Initial tests show that solutions based on Fresnel lenses for such applications should be "*feasible with today`s technology*".

For the aluminium casting discussed in the chapter "*Aluminium Casting in Regolith*", moulds from regolith simulants are required. While the cast aluminium would be recycled from space debris, the question remains how the mould can be optimally produced on the Moon.

Sand-casting is one of the oldest and today most commonly used methods for metal casting.[224] As the name implies, this method uses *green sand*, also called *moulding material*, to create a mould from a pattern. For sand casting, no special preparation of the regolith is required. The experiments by Baasch, TU Braunschweig / TU Berlin show the possibility of using regolith directly as a substitute for mould material. The regolith is only slightly compacted, and the cast models are pressed directly into the simulants and removed again. The resulting (negative) form is then filled with molten aluminium. After cooling, the cast can be easily removed from the mould. The sand-casting process can be fully automated, which makes sand-casting the ideal process for lunar manufacturing.

Another method is the *permanent mould casting* method. It uses multi-part permanent moulds that can perform several hundred castings. For this purpose, the compacted regolith mould is first sintered to achieve a permanent shape. Typically, the mould is sintered for 1h inside a high-temperature oven at about 1,100 C. Due to the sintering process, the tensile strength increases sharply, and the mould gets a brick-like hardness. The advantage of sinter moulds is the finer cast structure, such as the experiments of Baasch et. al. show.

Like on Earth, the sintering of the moulds could take place on the Moon with electric furnaces, e.g., powered by solar panels. But in addition to this extra equipment, which must also be transported to the Moon, the main limitation of a furnace solution would be the size limitations of the moulds.

Alternative solutions for sintering regolith were successfully investigated, which could be adopted for the mould generation. Ghosh and Prof. Favier from the International Space University published the results of their preliminary experiments "*Solar Sintering on Lunar Regolith Simulant (JSC-1) for 3D Printing*"[225] at the IAC 2016. They produced fused metallic glass objects made of regolith simulant (JSC-1) using a solar sintering technique and demonstrated the possibility of developing components made of regolith and other materials with concentrated solar energy. A single Fresnel lens with a surface area of 0.7 m^2 was used, which generated a sufficient amount of energy to melt regolith simulant (JSC-1).

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[224] Regolith as substitute mold material for aluminium casting on the Moon

[225] Solar sintering on lunar regolith simulant (JSC-1) for 3D printing - IAC 2016

Comparable results were achieved by Alexandre Meurisse, Advenit Makaya, Christian Willsch and Matthias Sperl from DLR, Germany and ESA-ESTEC, The Netherlands.[226] By using similar simulants (JSC-1A and JSC-2A), the authors combined concentrated sunlight with a 3D printing process to create the first 3D printer capable of generating three-dimensional objects from lunar regolith simulant. The experiments took place in the solar furnace facility of DLR-Cologne, Germany. The *High-Flux Solar Furnace*, commonly called solar oven, consists of a 52m² flat mirror, the heliostat, which tracks the Sun and reflects the light onto a concentrator of 147 mirror facets, whereby the light is focused in the laboratory. Figure 58 shows the setup.

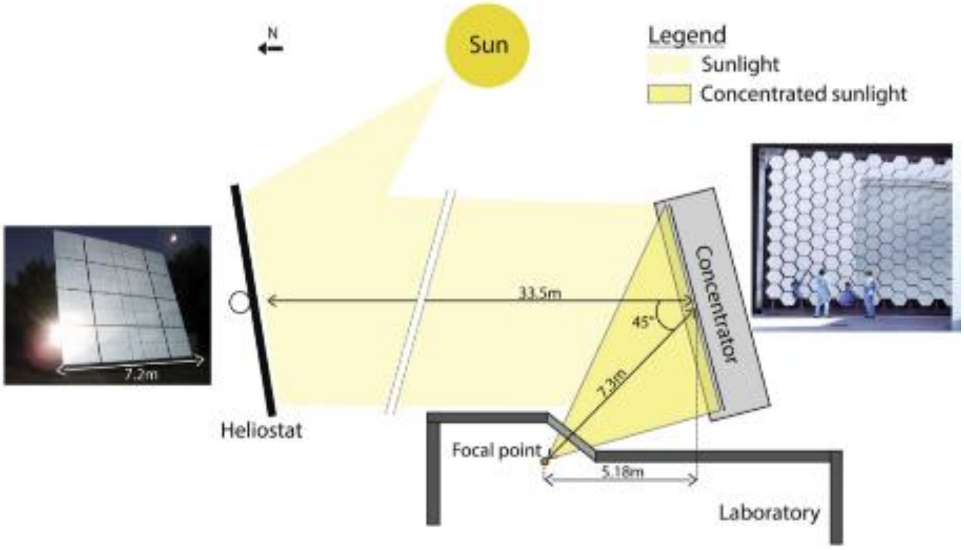

Figure 58: DLR sun furnace concept Cologne, Germany (Meurisse, Makaya et. al. (226))

In their work, the feasibility of sintering lunar regolith layer by layer was demonstrated solely using concentrated sunlight. However, the current compression strength of the regolith material produced does not yet allow application for direct construction purposes on the Moon.

Instead, Orbit Recycling proposes the combination of both techniques: regolith sintering using concentrated sunlight to create large moulds and cast aluminium with these moulds. The achieved cast aluminium would have the required strength and material properties for the desired lunar constructions.

Preliminary tests by Orbit Recycling with a Fresnel lens of 40cm x 40cm show promising results. The sharp lens focus has a diameter of less than 5mm and achieves a flux density of several MW/m² in Berlin, Germany with an average daylight flux density of ~1,000 W/m². In the focus, temperatures of more than 1,300°C were measured. Under these conditions, various regolith simulants were successfully sintered and instantly glazed, and aluminium probes of 1cm x 1.5cm x 3mm melted in seconds. The following images show the experimental lens structure as well as its sharp focus, which is visualized by means of water spray.

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[226] Solar 3D printing of lunar regolith

Figure 59: 40cm Lens experiment (Orbit Recycling)

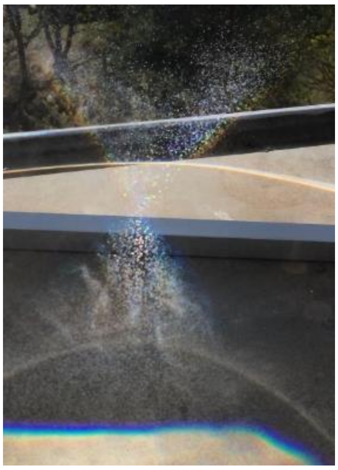

Figure 60: Visualizing of the lens focus with water (Orbit Recycling)

Due to its low weight of less than 500 g, the idea of Orbit Recycling is to use the small lens as a mobile lunar sintering solution. For this purpose, the lens would be attached to a lunar rover, like the previous discussed PHASR (s. chapter "*Recovery of Space Debris Fragments after Impact*"). Such a concept is currently being investigated between Orbit Recycling and PTS, Berlin and Orbit Recycling and WARR e.V., Munich.

The WARR e.V. rover will be tested at the IGLUNA challenge 2021[227] to demonstrate its ability of regolith sintering in the field. IGLUNA is an interdisciplinary platform where students from worldwide universities design and collaborate on innovative projects for the future of space exploration. The WARR e.V. rover uses a standard 6-wheeled rocker-bogie drive system design and the payload is mounted using a horizontal 2-axis gantry as the interface. This allows for planar movement in two orthogonal directions of the Fresnel lens. Focused sunlight from the lens can therefore be moved along the sintering plane.

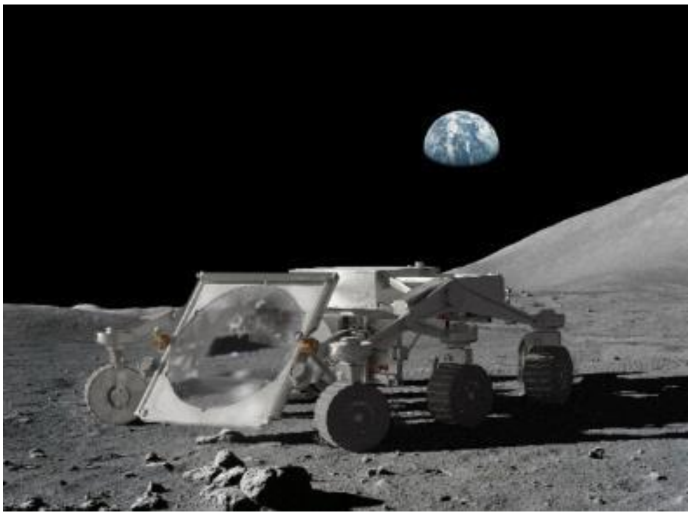

Figure 61: Exemplary design of a "sinter-rover" (WARR e.V., Munich, partner of Orbit Recycling)

More information about WARR e.V. the IGLUNA challenge and the collaboration with Orbit Recycling can be found in the appendix at "*Introduction WARR e.V.*".

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[227] IGLUNA 2021: Project Team 11 "rebels"

In addition to the mobile solutions for Fresnel lens regolith sintering, Orbit Recycling is also evaluating possible stationary lens concepts. For this purpose, a 110cm lens is used. Thanks to the larger surface, more energy is available in the focus to heat a larger amount of aluminium or regolith faster. Together with Collin Bolt, University of Waterloo, Canada, a first concept of such a stationary solution was visualized, as shown below. The concept is optimized for the lunar South Pole region, where the Sun would be positioned deep above the horizon.

Studies by ESA show that at a height of 2m in the lunar South Pole region, sunlight should be visible 85% of the year.[228] A mirror is used and dimensioned accordingly to redirect the sunlight vertically across the lens. To keep the mirror at the minimum height of 2m above the ground (including 130cm focus length of the lens), an extendable arm is used. This construction achieves the same light flux at the lunar South Pole as at the equator, since due to the lack of atmosphere on the Moon there is no weakening of the light.[229]

Figure 62: Lens with reflecting mirror (Bolt, Orbit Recycling)

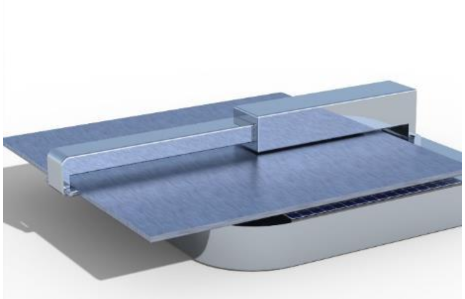

Figure 63: Folded lens and mirror for transport (Bolt, Orbit Recycling)

The “*massive*” stand makes it possible to adjust the lens vertically by +/-10cm, so that the lens focus can be easily aligned to different ground levels. Solar panels are mounted around the lens to generate the energy the motors need to raise and lower the lens and the top mirror and rotate the mirror structure to the sun. The entire structure can be folded for easier transport to the Moon and would be installed on a rail structure to move over the lunar surface like a large plotter. This allows the generation of large moulds needed for the lunar station (Figure 55) of 4m x 5m or larger. Figure 64 visualizes the concept.

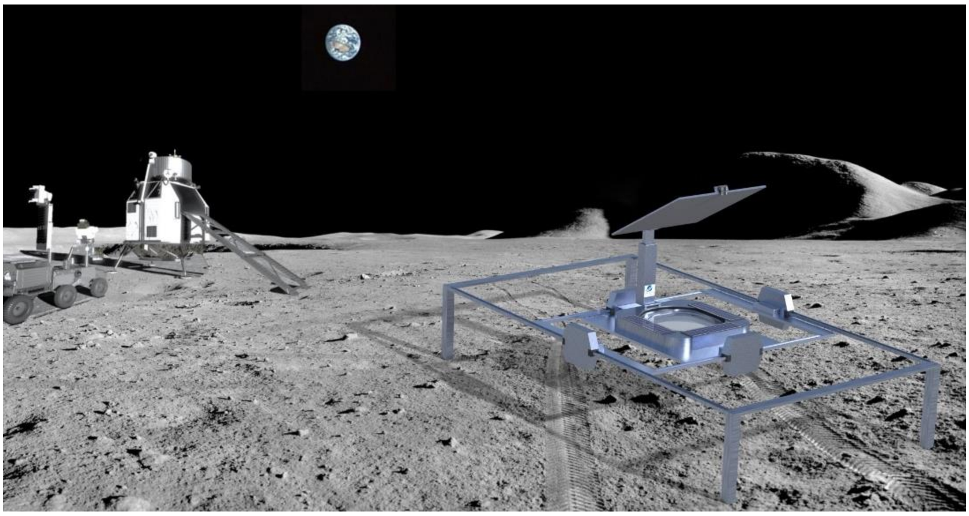

Figure 64: 110cm lens with mirror on slider and rails for stationary usage (Bolt)

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[228] Analysis of landing site attributes for future missions targeting the rim of the lunar South Pole Aitken basin

[229] Only losses through the mirror and lens material would occur, typically in the range of 5-10%.

To validate the concept of sintering regolith only with concentrated sunlight, Frank Koch, Orbit Recycling compared his experimental results with other studies in this field. In Germany, the *LASER Zentrum Hannover* (LZH) and the TU Braunschweig conducted experiments with LASER technology to sinter various regolith simulants. Under the project name *Moonrise,*[230] publications can be found that discuss the results achieved.[231]

During the *Moonlight* experiments, a LASER beam of typically 70 W (up to 140 W) is directed for 6 sec to a fixed spot on the regolith surface. An *engineering model* (EM) has been built and tested for functionality under varying environmental conditions, including tests under vacuum and lunar gravity conditions in the large-scale research device *Einstein-Elevator* in Bremen, Germany. In addition, the EM was accommodated on a robotic arm. Solid 2D structures of 20 mm x 20 mm x 4 mm in size were generated reproducibly despite the inhomogeneous simulant material.

The following images compare the sintering results of the LZH`s *Moonlight* LASER experiments with the first solar sintering experiments with Fresnel lenses by Frank Koch, Orbit Recycling. Figure 65 shows the LASER-sintered regolith simulant results of Neumann, LZH on the left, while Fresnel lens sintered regolith simulant is shown on the right. Initial indications show that both solutions would be practicable options for the successful sintering of regolith, e.g., for the production of (aluminium) moulds.

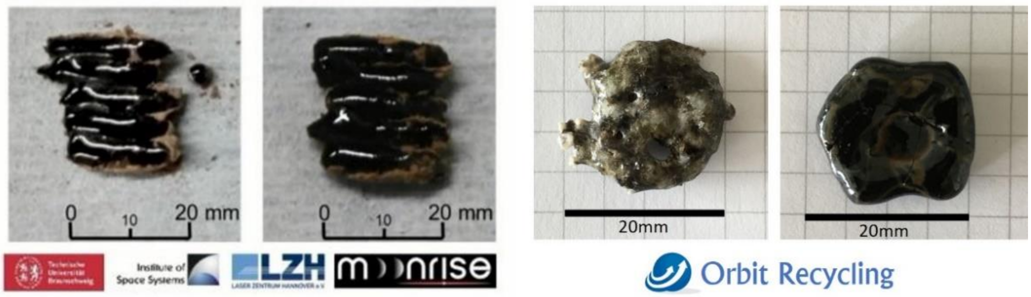

Figure 65: Sintered regolith simulant TUBS-M / TUBS-T (Neumann, LZH, Orbit Recycling

However, the potential of solar regolith sintering is not limited to mould production. Since regolith is extremely "sticky" and adhesive, glazed regolith surfaces would reduce the risk of dust contamination for any (moving) object. After their surface missions, the Apollo astronauts found regolith on their space suits everywhere and brought it back to their landers, causing symptoms such as a dry cough or worse. In addition, the sharp edges of the regolith damage rover wheels over time and creep into any housing, as experienced in terrestrial regolith test environments. This reduces the overall lifespan of mechanical machines on the Moon. Sintered and glazed paths would limit these risks by reducing the amount of dust and levelling the surfaces for any wheels.

Second, loose regolith material would be blown away from the exhausts of a lander propulsion system. If the landing site had been glazed in advance, smaller or even no regolith dust storms would occur. Based on initial experiments, Orbit Recycling designed a concept of a light rover with 16 lenses of 40cm x 40xm each. Each lens can sinter at least 4cm² per minute, resulting in about 9m² of glazed surface per 24 hours, without the need for additional (electrical) power beside for the rover itself. Since each lens weighs less than 1 kg (on Earth), individual solutions for even small rover platforms could be designed.[232]

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[230] Project Moonrise - LZH

[231] Press releases Moonrise - LZH

[232] Planetary mobility - Astrobotic

RECOMMENDED NEXT STEPS

Regolith sintering through concentrated sunlight, e.g., with Fresnel lenses, seems to be a promising way to create large moulds for aluminium casting on the Moon. In addition, surfaces such as pathways or landing sites could be glazed to prevent dust storms and contamination by regolith grains. This protects all mechanical structures from damages caused by the highly adhesive, sharp regolith particles.

Additional experiments should be carried out with different regolith simulants and under vacuum conditions to validate the achievable mould structures as well as the expected glazed areas per hour. With the support of ESTEC`s technical capabilities, various Fresnel lens materials were to be examined for their use under lunar conditions (radiation, temperature etc.). This includes testing a simple but effective glass-encapsulating concept of the acryl lenses currently in use, provided by Orbit Recycling. Finally, in addition to the prototype for the IGLUNA 2021 challenge of Orbit Recycling`s partner, WARR e.V., further rover tests with lenses were to be carried out.

In addition to regolith sintering, Orbit Recycling conducted initial tests to melt aluminium through concentrated sunlight, too. With appropriately sized Fresnel lenses, there would be enough light flux energy to melt substantial amounts of aluminium. Additional tests should be carried out to validate these preliminary results. Above all, the simulation of the lunar environment conditions will be crucial, as the aluminium would melt under vacuum conditions, where cooling would only be carried out by thermal radiation. And without oxidation of the casting surface, positive effects of the achievable cast quality are expected. Special material research studies on this topic are recommended as part of a joint PHD with ESA.

PART 3

Business Case Estimation

A BUSINESS CASE FOR SPACE DEBRIS

CHAPTER SUMMARY

An initial cost estimate of recycled aluminium on the Moon is made, including the cost of the required space tugs, the lunar melting and casting infrastructure, and mission cost. Frank Koch, Orbit Recycling concludes that the cost of recycled aluminium would not exceed 150,000 Euro per kilogram, which is cheaper than current commercial or institutional alternatives from Earth.

In addition to cost reductions, the reduced risks to space activities in general are highlighted by the removal of large pieces of space debris. An LCA study is proposed to validate the identified benefits and verify the sustainable nature of the recycling concept for space debris.

The following table compares the cost of 100 tonnes of aluminium to-be-delivered to the surface of the Moon in different landers with the same amount of recycled aluminium from space debris. All "*lander scenarios*" include the total delivery cost of the payload to the surface, excluding the negligible cost for the aluminium itself of around 2,000 euro per tonne.

Currently, there are only few commercial lander-offers for Moon transports. On average, smaller landers with a payload of up to 200 kg cost around 1 million euro per kilogram of payload.[233] Even if this price can be reduced by 50% in the future, it would still cost 500,000 euro per kilogram, or more than 500 million euro per tonne.

This commercial offer is compared with the (institutional) alternative of the *European Large Logistic Lander* (EL3), which is being developed by ESA. ESA calculates a total cost of 750 million euro for around 1.5 tonnes of cargo in its EL3 program, which corresponds to 500,000 euro per kilogram for a delivery to the Moon.[234]

With the upcoming *Space Launch System* (SLS) in its original version, NASA estimates that it will initially deliver 4 tonnes of payload to the Moon with a "*targeted*" launch price of 800 million euro.[235] This price does not include the cost of the required lander itself. In a later version of the SLS, payload capabilities will be increased to 20 tonnes, although no development of the enhanced version of the SLS has begun and no cost estimates could be made for this expansion. Although the actual delays of the SLS program have already doubled the SLS launch price, the following comparison uses the "*official*" price of 800 million euro, INCLUDING a yet-to-be-developed lander.

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[233] Payload Configuration - Astrobotic

[234] *ESA European Large Logistic Lander (EL3)* – ESA Industrial Day 23/4/2020, EMITS / ESA-STAR

[235] Space Launch System - Wikipedia

	Small Commercial Lander	EL3 Cargo Mission	SLS 1.0 Mission	Recycling Mission
Payload / Recycling mass	200kg	1,500kg	4,000kg	2,200kg
Number of missions for 100-tonne aluminium	500	67	25	55
Price per tonne to the Moon / per recycling tug	1 billion (1 million per kg)	500 million (750 million per 1.5 tons)	200 million (800 million per 4 tons)	150 million
Avg. launch cost per mission	Incl.	Incl.	Incl. (800 million)	60 million
Mission operation costs	1 million	1 million	1 million	4 million
Total price for 100 tonnes	**100.5 billion**	**50.3 billion**	**20 billion**	**11.77 billion**
Costs for Moon infrastructure				50 million
Replacement costs (= 1 EL3 mission)				750 million
No. of replacements over 10y recycling time				2 (5y) 5 (2y)
Total costs recycling infrastructure over 10y				**1.6 billion (5y)** **4 billion (2y)**
Total price per option	**100.5 billion**	**50.3 billion**	**20 billion**	**13.4 billion (5y)** **15.8 billion (2y)**
Price per kg Al	1 million	503,000	200,000	134,000 158,000
Max. Savings	**87.1 billion** **84.7 billion**	**36.9 billion** **34.5 billion**	**6.6 billion** **4.2 billion**	/

Table 14: Business Case Calculation

For the scenario of space debris recycling, Orbit Recycling estimates the cost of a recycling space tug at around 150 million euro. This tug should be able to transport a 3.7-tonne upper stage from its GTO-location to the Moon. The price corresponds to the costs of comparable space servicing offers such as the MEV from Northrop Grumman[236] or the AGORA concept[237] of around 100 million euro and adds up the cost for e.g., Momentus` water-plasma propulsion unit for the lunar transit of 50 million euro. With a series production of up to 55 recycling tugs, the total unit price is to be further reduced to around 100 million euro per tug.

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[236] Space Logistics Services - Northrop Grumman

[237] Agora Mission to demonstrate technologies to actively remove Ariane rocket bodies

Since a recycling mission is more complex and has a longer flight time, the individual mission costs are increased by a factor of 4 compared to the direct deliveries of the other landers.

For the comparison, the scenario assumes 55 recycling tugs of 150-million-euro each, without considering scaling effects. The individual launch costs are estimated at around 60 million euro for an Ariane 64 as a secondary payload or 120 million euro for a dedicated launch with two recycling space tugs. A total of 121 tonnes of aluminium will be brought to the Moon (2.2 tonnes of aluminium per upper stage), of which 100 tonnes of aluminium will be recovered through the recycling process (a recovery rate of 80% of the impact fragments).

In addition to the recycling tugs, Orbit Recycling needs an infrastructure on the Moon for aluminium recycling. This includes two PHASR rover for collecting the aluminium fragments and solar-powered melting furnaces / lenses. Smith prepared some cost estimates based on the (limited) public information available totalling 50 million euro for this infrastructure (p. 78 of this study). Rover as well as the other infrastructure will be delivered via a single EL3 mission at the above-mentioned delivery price of 750 million euro per 1.5 tonnes of payload. A lifetime of 2 years and a 5-year scenario for the infrastructure are assumed. With 6 recycling space tug missions per year, a total duration of 10 years could be achieved, resulting in two or five EL3 infrastructure deployment missions.

As shown in Table 14, the recycled material on the Moon can be offered at a significantly lower cost than material from Earth. The recycling mission scenario reaches a total price of 13.4 to 15.8 billion euro per 100 tonnes of recycled aluminium or 134,000 to 158,000 euro per kilogram, far below the alternative lander options.

Recently, SpaceX was selected to develop a human lander (Starship) for NASA, but the contract is currently pending due to interventions from competitors. Starship is said to have a payload capability of at least "*dozens of tons*" but uses a complex launch scenario: the actual lunar payload is launched on a dedicated Starship in LEO. This first Starship is refuelled by several additional Starship launches to finally be able to reach the Moon and land safely. This complex launch scenario as well as the extremely early-development-phase of Starship without possible final cost estimates make a price comparison with the other solutions currently impossible. Instead, the Starship price is estimated to reach 50% of the estimated SLS price.

At 50% of the estimated SLS price, the intended but unproven cost for the upcoming SpaceX Starship could provide an alternative to the recycling concept. But this direct transport of material from Earth would not lead to the active reduction of space debris in the Earth`s orbit, as the recycling mission concept will do. These indirect cost savings are not reflected in the total cost estimates.

In addition, no scaling effects for the recycling concept were considered. The price per tug for an order of 55 space tugs will be significantly lower than the estimated development costs of 150 million euro for the first tug. The same applies to the launch costs: if 55 Ariane launches were booked, the individual launch price would also fall. Finally, the recycling potential of the space tugs themselves is ignored. For each recycling tug, around 280 kg of additional aluminium could be recovered. With 50 space tugs, this amount adds up to a further 11 tonnes (while maintaining the recovery rate of 80%), which further lowers the total price per kilogram of recycled aluminium. Some of these alternative scenarios are shown in Table 15.

(Recycling scenario A & B calculated with 80% recovery rate to reach 100 tonnes of aluminium from debris.)

	SCL with 50% cost reductions	**EL3 with 30% cost reduction**	**SLS 2.x with 20 tonnes payload**	**Recycling A (Incl. scaling effects)**	**Recycling B (incl. scaling & tug potential)**
Payload / Recycling mass	200kg	1,500kg	20,000kg	2,200kg	2,480 kg
Number of missions	500	67	5	55	50
Price per tonne to the Moon / per tug	500 million	150 million	(140 million)	100 million	100 million
Avg. launch cost per mission	Incl.	Incl.	2.8 billion[238]	40 million	40 million
Mission operation costs	1 million	1 million	1 million	4 million	4 million
Total price for 100 tonnes to the Moon	**50.5 billion**	**15.1 billion**	**14 billion**	**7.9 billion**	**7.2 billion**
Costs for Moon infrastructure				50 million	50 million
Replacement costs (= 1 EL3 mission)				225 million	225 million
No. of replacements over 10y				2 / 5	2 / 5
Total costs recycling infrastructure over 10y recycling time				**450 million (5y)** **1.1 billion (2y)**	**450 million (5y)** **1.1 billion (2y)**
Total price per option	**50.5 billion**	**15.1 billion**	**14 billion**	**8.4 billion (5y)** **9.1 billion (2y)**	**7.7 billion (5y)** **8.4 billion (2y)**
Price per 1 kg Al	505,000	151,000	140,000	84,000 91,000	77,000 84,000
Max. Savings vs. Recycling A	**42.1 billion** **41.4 billion**	**6.7 billion** **6.0 billion**	**5.6 billion** **4.9 billion**	/	
Max. Savings vs. Recycling B	**42.8 billion** **42.1 billion**	**7.4 billion** **6.7 billion**	**6.3 billion** **5.6 billion**		/

Table 15: Additional Business Case Scenarios

In the long term, Orbit Recycling`s vision foresees reusable recycling tugs that drop the upper stages on the Moon and would be refuelled at the Lunar Gateway. The tugs would then return to GTO to pick up the next upper stages, reducing the total cost per kilogram of aluminium recovered even further.[239]

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[238] SLS 2.x launch costs estimated to 2,8 billion incl. lander costs for 20 tonnes payload to the Moon. Estimation based on current budget spending according to Space Launch System (Wikipedia)

[239] This vision is not more ambitious than the vision of SpaceX` Starship concept.

RECOMMENDED NEXT STEPS

The current cost estimates are based on several, albeit fair, assumptions. To use them as an important criterion for deciding whether to carry out a recycling mission or to make further investments in this issue, these figures should be reviewed and re-validated.

In addition to direct cost savings as estimated in the table above, the recycling of space debris has a positive impact on the environment. Compared to small landers, the number of space missions is drastically reduced. And due to the simultaneous launch of two recycling tugs, the total number of launches corresponds to the super heavy SLS launcher. But the recycling tugs could be launched on Ariane 64, with less impact on the environment. This positive effect on the environment should be validated in a dedicated *Life Cycle Assessment* (LCA).

LCA is a methodology that makes is possible to determine environmental impacts such as climate change as well as the use of resources for products, technologies, and services over their life cycle. A comparison of the recycling approach with the alternative to transport aluminium from Earth would allow a conclusion to be drawn as to which design leads to lower overall impact on the environment. Other benefits such as no oxidation on the Moon must be integrated into the study to achieve a fair comparison.

Since aluminium is one of the materials with the highest environmental impacts, using secondary material of unused space technologies might already lead to less impacts compared to transporting primary aluminium from earth. In addition to the classical LCA impact categories for resource use such as fossil and mineral resource depletion which assess the geological resource availability, also short and middle-term socio-economic resource criticality should be considered. Even though aluminium is not one of the scarcest resources, it still faces supply risks such as trade barriers and being mined in political unstable countries. Thus, from a criticality point of view using aluminium of unused space technology will not decrease its availability on earth, which would be the case when aluminium is transported from the earth to the moon.

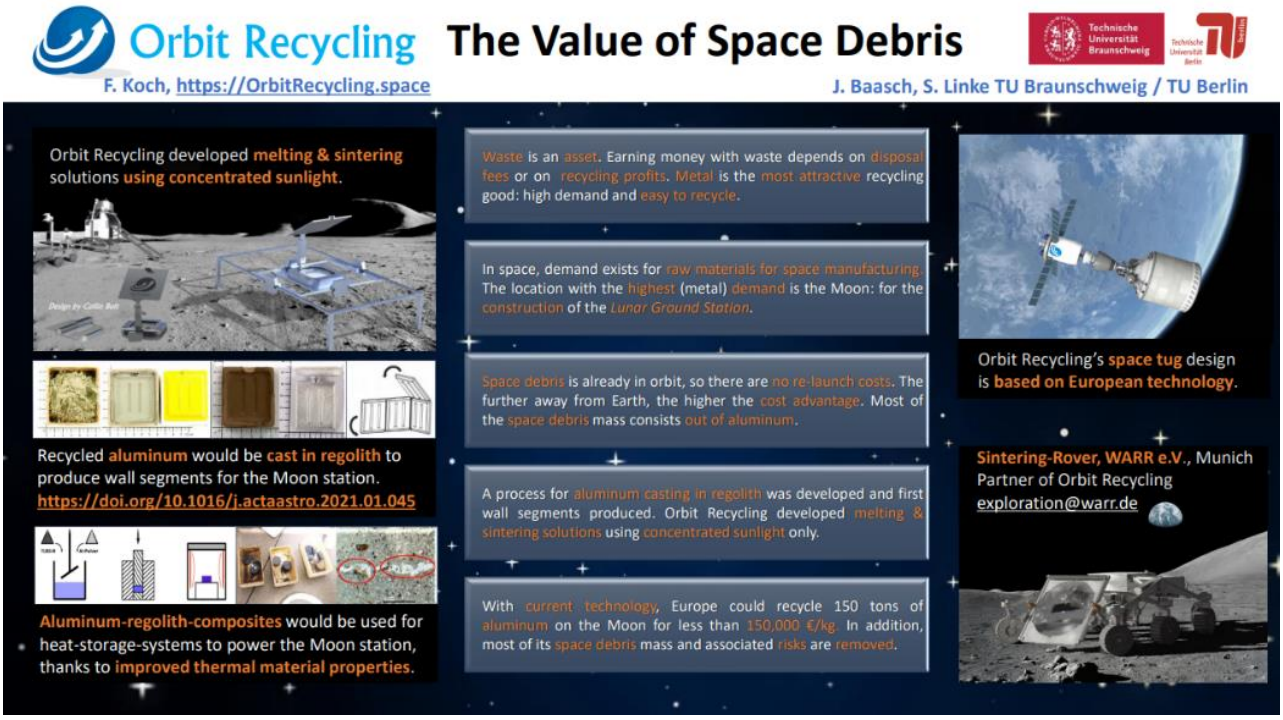
The result of the carried out LCA case study is to determine which technology leads to less environmental and resource use impacts as well as how they can be improved from an environmental and resource point of view. Orbit Recycling proposes the Chair of Sustainable Engineering at TU Berlin, Germany for the LCA. The proposed partner is described in more detail in the appendix "*Introduction TU Berlin - LCA of space debris recycling*".

SUMMARY AND CONCLUSION

“Where does Europe want to be in 15 years from now?” Josef Aschbacher asked this question when he was elected ESA Director General. In spring 2021, he worked with ESA`s Member States to set new priorities and goals for ESA for the coming years, which also means developing the kind of programmes and missions that ESA Member States can be proud of. The ESA Agenda 2025[240] outlines these challenges and mentions Europe’s ability to act sustainably and commercially in space: ESA will launch Europe and the world into the era of space logistics by developing in-space servicing, manufacturing, construction and recycling capabilities, including the exploitation of material space resources. Recycling of space debris would be the perfect showcase for this ambitious goal. Being first to recycle its own space debris, Europe could be truly proud of such a space mission.

As on Earth, space debris should not only be seen as a threat. Instead of insisting on removal fees, the value of waste as a recycled good should be understood. As highlighted in this study, the recycling of space debris is a challenge, but within the framework of Europe`s technical capabilities. The recycling of raw materials for space manufacturing seems to be the initially low-hanging fruit and objects with a high aluminium content are the ideal recycling target.

The demand for recycled aluminium is driven by the construction of the *International Lunar Ground Station*. Since the transport of materials to the Moon remains expensive and *In-Situ-Resource-Utilization* as an alternative supply is not yet mature enough, a recycling mission with the estimated price of 150,000 euro per kilogram of aluminium on the Moon should at least be cost-competitive.



Orbit Recycling The Value of Space Debris

F. Koch, https://OrbitRecycling.space

J. Baasch, S. Linke TU Braunschweig / TU Berlin

Orbit Recycling developed melting & sintering solutions using concentrated sunlight.

Recycled aluminum would be cast in regolith to produce wall segments for the Moon station. https://doi.org/10.1016/j.actaastro.2021.01.045

Aluminum-regolith-composites would be used for heat-storage-systems to power the Moon station, thanks to improved thermal material properties.

Waste is an asset. Earning money with waste depends on disposal fees or on recycling profits. Metal is the most attractive recycling good: high demand and easy to recycle.

In space, demand exists for raw materials for space manufacturing. The location with the highest (metal) demand is the Moon: for the construction of the *Lunar Ground Station*.

Space debris is already in orbit, so there are no re-launch costs. The further away from Earth, the higher the cost advantage. Most of the space debris mass consists out of aluminum.

A process for aluminum casting in regolith was developed and first wall segments produced. Orbit Recycling developed melting & sintering solutions using concentrated sunlight only.

With current technology, Europe could recycle 150 tons of aluminum on the Moon for less than 150,000 €/kg. In addition, most of its space debris mass and associated risks are removed.

Orbit Recycling’s space tug design is based on European technology.

Sintering-Rover, WARR e.V., Munich
Partner of Orbit Recycling
exploration@warr.de

Figure 66: The Value of Space Debris, Frank Koch, Orbit Recycling[241]

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[240] Introducing ESA Agenda 2025 - ESA

[241] The Value of Space Debris , 8th European Conference on Space Debris 2021

Together with its research partners, Orbit Recycling has demonstrated the feasibility of aluminium casting in regolith and shown that the lunar manufacturing of large wall segments and small objects for the Moon station from space debris is not only possible, but also cost effective and efficient. In addition, Europe is removing a large part of its entire space debris mass from Earth`s orbit, thereby reducing the overall risk of collision for all other space activities.

Additional research is needed to mature the concept presented and close certain capability gaps. However, since most of the required technology already exists or is currently being developed for other space missions, many synergies could be exploited to reduce the remaining realization budget. The following is a shortened list of relevant activities and identified synergies from this study.

IDENTIFIED SYNERGIES AND RECOMMENDED ACTIVITIES FOR SPACE DEBRIS RECYCLING

1. To identify the ideal recycling targets, a detailed catalogue of space (debris) objects, including material composition and used components must be created.
    a. European data sets such as DISCOS should be extended by the missing object information. Since this is required for all future space servicing mission, there are no additional costs for space debris recycling.
2. Ground observation of target objects should be carried out to track their trajectories and tumbling behaviour.
    a. Europe has a large amount of data available. However, light curve measurements should be combined with RADAR / LASER observations to generate even better data sets which are analysed via machine learning algorithms to simulate the rotation behaviours. The underlying simulations and rotation models would be beneficial for all types of object movement predictions, especially for complex trajectories of the space servicing mission in GTO, where space debris recycling could also benefit.
3. (Contactless) Detumbling technologies must be evaluated and matured for use in space.
    a. The first theoretical foundations exist in Europe, but they need to be improved. Europe must catch up with the US and Japan to develop its own detumbling solution for uncontrolled space objects, if space servicing missions are to be carried out from Europe. Various coil designs and materials should be evaluated for their effectiveness. Space debris recycling could benefit directly from these developments.
4. Gripping technologies must be evaluated and matured for use in space.
    a. Existing tools such as the *European Robotic Arm* and the upcoming *ClearSpace-1* solution should be examined for their general reuse & scaling potential for space servicing missions, where recycling could also benefit from.
5. For material transports from the Earth (orbit) to the Moon, various space tug concepts are required.
    a. Depending on the application, fast but expensive solutions or slow but more cost-effective solutions are used to supply the upcoming Lunar Gateway as well as any lunar ground station. A CDF is proposed to discuss these contradictive requirements. The technology to-be-developed for theses supply tugs could be the basis for space servicing mission as well as for space debris recycling tugs.
        i. Existing development in the field of propulsion technology such as AVUM+, Space Rider, ESM/ATV and others could be shared between the different scenarios of lunar supply, space servicing and space debris recycling.
        ii. The technology developments of the GNC / AOPS components (e.g., *Clerarspace-1*) could be shared between the scenarios of lunar supply, space servicing and recycling.

        iii. Communication infrastructure and ride-share launch technology could be shared between the different scenarios of lunar supply, space servicing and recycling.
        iv. Trajectory calculations for optimized Moon transits (e.g., EL3) could be used for the upcoming lunar supply missions as well as the recycling missions.

6. The European Moon lander (EL3) could be shared between the currently planned lunar supply and research missions as well as for the transport of the recycling infrastructure to the Moon.
    a. EL3`s cargo capabilities should be evaluated against the recycling infrastructure requirements to identify potential limitations in the current design phase of EL3.
    b. Lunar impact simulations should be performed to better understand the effects of a failed EL3 mission. Space Debris recycling could directly benefit from the impact simulation results for its own concept of material transports to the Moon.
7. Planned lunar rover (such as PHASR) should be evaluated for their potential for use in collecting debris fragments from the lunar surface and for transporting them to the recycling station.
    a. These include the rover itself, its power supply, any manipulators, cameras, and sensors, as well as the transport capabilities to identify limitations and the necessary (minor) modifications for a dedicated recycling version of the rover.
    b. The transport of the rover to the Moon as well as any necessary communication infrastructure to control the rover should be evaluated for the potential use of the EL3 during the planned recycling missions.
8. Additional studies should be carried out on aluminium casting on the Moon, where Europe could become a world leader in lunar manufacturing. Even if it were not used for the recycling of space debris, it would also allow the production of local large objects derived from ISRU aluminium.
    a. Synergies in all areas (rover, furnace, power, communication, etc.) should be identified to minimize development efforts and costs.
    b. The sintering of regolith moulds and aluminium casting capabilities should be aligned with the requirements of the upcoming lunar ground station.
        i. The recycling concept enables various expansion stages of the recycling infrastructure as well as the removal of debris. The casting capacity could be scaled by 2 tonnes to 14 tonnes per year to meet the annual supply demand during the station construction.
        ii. In addition to space debris, EL3 lander modules and rovers could also be recycled.
        iii. By-products of the oxygen production from regolith such as aluminium and other metals should be evaluated for their use as an additional casting material.
    c. In addition to the recycling concept, Fresnel lenses could be the most energy-efficient way to sinter and glaze large surfaces on the Moon. This avoids dust clouds and rover wheel damages at frequently used passages (e.g., between the landing site and habitat). Further tests should be carried out to validate this concept.

Frank Koch, Orbit Recycling has built up a network of renowned research and industry partners in recent years with the necessary skills and abilities of the above-mentioned areas. These partners are described in the appendix to emphasise that Europe can carry out a mission to recycle space debris.

All it takes is the political will to “*Turn Waste into Value*”.

APPENDIX

OVERVIEW STUDY PARTNERS

INTRODUCTION ORBIT RECYCLING

Orbit Recycling[242] offers a sustainable approach to the supply of building materials in space based on recycled space debris. This globally unique approach addresses pressing societal challenges such as environmental protection and sustainability, as well as the reducing the risk of debris collision for all other space activities.

During his physics study, Frank Koch founded his first company with a focus on "*hazardous waste treatment*". He later worked for Microsoft and Samsung in positions of international responsibility and became a national sustainability leader for Microsoft Germany, before entering the space industry and presenting preliminary talks on the recycling of space debris. Since 2015, Frank Koch has been working as a freelancer in Berlin on the “Orbit Recycling” concept to bring sustainability into space.

Orbit Recycling develops new concepts for building materials on the Moon. Together with its broad network of institutional research partners, innovative technologies were developed and unique methods for the use of regolith as building material for a future Moon station were investigated. The results were presented at the ESA Space Industrial Debris Days in ESTEC, the Netherlands and the Space Resources Week 2019 and 2021 in Luxembourg.

In 2020, Orbit Recycling was awarded the "*Most Pioneering Aluminium Recycling Company*" award by the *build magazine* for its concept, and in 2021, *Corporate Lifewire* awarded Orbit Recycling the title “*Most Innovative Recycling Business*”.

The Orbit Recycling logo represents two stylized objects orbiting the Earth (e.g., a debris object to be recycled and a recycling space tug). It is reminiscent of the logo of the *Duales System* (“*Grüner Punkt*”) and transmits it into space through the color of blue. The aim is to establish the logo as an international standard for space debris activities. Future rockets or satellites shall use this logo to express their later recycling possibilities.

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[242] Orbit Recycling Homepage

INTRODUCTION TU BRAUNSCHWEIG / TU BERLIN

At the TU Braunschweig, the Institute of Space Systems the group Exploration and Propulsion Systems is established. Its goal is the development of new exploration systems, *In-Situ-Resource-Utilization* (ISRU) technologies, ISRU based materials and lunar science payloads as well as propulsion systems for small satellites for the space industry. Since the transition of Prof. Enrico Stoll to the TU Berlin at the beginning of 2021 and taking along of projects, the group decided to move completely to TU Berlin. All ongoing and future projects are moving to TU Berlin during this year with the current group to be re-established there.

The working group focuses on the development of the Moon for scientific and economic purposes and the use of local resources. To have a suitable raw material, own synthetic lunar soils (simulants) are developed and produced, which reproduce the lunar regolith at every known point regarding chemical and physical properties. The basic components consist of two basic simulates **TUBS-M** and **TUBS-T**. TUBS-M represents the mare of the Moon and consists of mainly of basalt, while TUBS-T represents the highlands and consists mainly of anorthosite.

For the planned Moon-village of ESA considerable amounts of resources are required to build the necessary infrastructure on the Moon. To keep the transport costs as low as possible, the local raw materials of the Moon should be used as much as possible. Many of the required elements are contained in the surface material of the Moon, the so-called regolith. Regolith consists, among other things, of oxides of silicon (Si), iron (Fe), aluminium (Al) and magnesium (Mg). To make the elements usable for machine parts, for example, the metals must be extracted. These processes are complex and require many additives that must be transported from the Earth to the Moon. In the **ELMORE** project, the elements are to be extracted using electrochemical processes without additives.

Further discussed methods to obtain metals on the Moon are space debris as proposed by Orbit Recycling and metal-bearing meteorites. The extraction of these metals has two advantages compared to the electrochemical process. On the one hand, the material has a high metal content, which means that processing is low. On the other hand, the debris and meteorite fragments are easily accessible because they are stored on and close to the surface in the loose regolith. Due to the metal content, the induction method, which is also used on earth to search for metallic objects lying in the ground, is suitable for the detection. In autumn 2020, a test campaign was carried out with an experimental rover, which was equipped with a device for metal detection based on the induction method. The rover drove through the test area autonomously and was able to detect numerous metal objects and mark them on a digital map.

The working group also researches manufacturing techniques with the extracted metals. Tests on adaptive casting techniques were carried out in collaboration with Orbit Recycling. The moulds, which consist of sand, binder, and additives (or metal) in classic casting processes, were replaced by regolith simulant. To adapt the sand-casting process, the simulant was either melded directly, or melded and sintered, resulting in a stable mould, comparable to the permanent mould casting process. With these moulds, aluminium parts were successfully cast.

The working group has extensive experience in handling and processing lunar regolith. In the **3D4Space** project, the foundation stone for the development of a high-temperature print head was laid with the demonstration of melting lunar regolith simulations and the processing of regolith-polymer compounds was investigated. Different methods to produce semi-finished products from sintered lunar regolith and systems for conveying in extrusion units were considered. Based on the results of **3D4Space**, the focus of the current research project **EDAM-R** is on the additive manufacturing of structures with molten lunar regolith under vacuum conditions.

To prove the feasibility of LASER melting on the lunar surface, the group is developing the **MOONRISE** experiment together with the LZH as part of a project funded by the Volkswagen Foundation. A compact LASER system is to be transported to the surface of the Moon by a commercial lunar lander in the next few years. Once there, the LASER is activated and melts the regolith directly below the experiment. The **MOONRISE** experiment is currently being tested in practice. At the beginning of 2020, melting tests were carried out in the laboratory under 1 g of gravitational acceleration, in the Einstein Elevator (EE) under 0.16 g (lunar gravity) and in free fall (microgravity) using a regolith simulate developed in-house.

To survive the long lunar night the lunar base and the robotic systems needs large energy reserves which must be stored during the lunar day. As regards the use of local resources, the uses of the existing regolith as heat storage are investigated. Since the regolith has an unfavourably low thermal conductivity, research is being carried out within the working group in cooperation with Orbit Recycling on regolith-aluminium composites, which are more suitable as heat stores due to their increased thermal conductivity. This investigation is to be examined more intensively and further developed as part of an **ESA-funded PhD**.

Another essential requirement for energy is given for the transport of goods from the earth to the moon, back and to the planned station in lunar orbit. This energy is needed in chemical form for rocket propulsion. Studies show that if the fuel for the return flight is obtained on the Moon and made available in a “rocket filling station”, the overall system can already shrink down significantly. Therefore, the working group, in cooperation with research partners, is looking at the possibilities of providing fuels on the moon and using them for a closed logistics chain from earth via a station in lunar orbit to a station on the lunar soil for goods and people.

INTRODUCTION TU BERLIN - LCA OF SPACE DEBRIS RECYCLING

As space activities generate pressures on the environment as well as on resources, there is a growing necessity to assess space activities and technologies comprehensively and consistently with Life Cycle Assessment (LCA). LCA is a methodology allowing to determine environmental impacts such as climate change as well as the use of resources for products, technologies, and services over their life cycle. Thus, a novel LCA case study must be carried out, identifying environmental and resource related hotspots and improvements. Further, a comparison of this approach with the option to transport aluminium from Earth would allow for deriving a conclusion which design leads to less overall environmental impacts.

For a just comparison, the technology’s’ function is set to produce 1 tonne of aluminium but can be scaled to aluminium outputs fewer or higher than 1 ton. Further advantages like no oxidation on the moon must be integrated into the study to achieve a fair comparison.

Next, the life cycle of both technologies (design phase, manufacturing, utilization and disposal) needs to be modelled, e.g., considering the energy used for operating the technologies as well as for their manufacturing. Thus, first primary data for the two mission design technologies is collected, which is complemented by secondary data from literature and LCA databases. Considered environmental impacts should include climate change (closely related to energy use) as well as acidification and eutrophication (related to constructing the used technologies on earth). As aluminium is one of the materials with the highest environmental impacts, using secondary material of unused space technologies might already lead to less impacts compared to transporting primary aluminium from earth.

Next to the environmental impacts, a focus also is on the assessment of resources. In addition to the classical LCA impact categories for resource use such as fossil and mineral resource depletion which assess the geological resource availability, also short and middle-term socio-economic resource criticality should be considered. Even though aluminium is not one of the scarcest resources, it still faces supply risks such as trade barriers and being mined in political unstable countries. Thus, from a criticality point of view using aluminium of unused space technology will not decrease its availability on earth, which would be the case when aluminium is transported from the earth to the moon.

The result of the carried out LCA case study is to determine which technology leads to less environmental and resource use impacts as well as how they can be improved from an environmental and resource point of view.

CHAIR OF SUSTAINABLE ENGINEERING

The Chair of Sustainable Engineering (SEE) aims at the realisation of sustainability by developing and applying assessment methods in the context of technology and sustainability. Therefore, SEE bridges the gap between research and application and supports the integration of sustainable development into daily engineering practice by providing the right methods and tools. It is recognised internationally as one of the leading institutes in the fields of environmental and sustainability assessment. SEE is currently working on over 20 projects for various sectors, e.g., mobility, buildings, food, energy, textile, chemicals, retailers, etc.

Regarding the specific content of this project SEE has the following expertise: it carried out over 100 LCA case studies for a variety of technologies, services, and products, e.g., mining and processing of metals[243,244]. Further, the methodological development of LCA[245], including the carbon footprint[246] as well as improvement of impact assessment methods for a variety of impacts, e.g., biodiversity[247] and water scarcity[248] is a focus of the research group. Further, SEE conducts research for the assessment of resource use e.g., development of an integrated method to assess resource use impacts (ESSENZ)[249] to consistently determine geological availability and scarcity aspects of resources in line with sustainable development, and the implementation of these methods in LCA by carrying out a variety of case studies e.g., for the mobility sector[250,251]. Further, Prof. Finkbeiner has more than 20 years of experience in accomplishing and validating LCAs as well as LCA method development and has been appointed for several policy relevant committees and projects, like the International Life Cycle Board (ILCB) of the UNEP Life Cycle Initiative.

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INTRODUCTION MUSEUM FÜR NATURKUNDE – MFN (BERLIN)

The "Museum für Naturkunde – Leibniz Institute for Evolution and Biodiversity Sciences http://www.naturkundemuseum-berlin.de/en/) is a research museum within the Leibniz Association. As a major museum of Natural History, it is one of the most significant research institutions worldwide in biological and geo-scientific evolution research and biodiversity.

Besides a broad expertise in biodiversity and evolution of life research the museum also aims at constraining the effect of collision events on Earth's biosphere. The museum hosts one of the largest research groups specialized on meteorite impact processes and curates a collection of more than 4000 meteorites. The methods applied comprise geophysical exploration of the crater subsurface, geological field studies at terrestrial craters, mineralogical and chemical analyses of rocks and minerals, as well as computer simulations and laboratory shock experiments. By means of an interdisciplinary approach including geology, mineralogy, geophysics, palaeontology, biology, and computer engineering impact events in Earth's history and their implications on the evolution of life are investigated.

Figure 67: Photograph of the main entrance of the Museum für Naturkunde (MfN) Berlin

The study of impact processes and meteorites is one of the main research fields at MfN for more than 30 years. Many research projects on this topic funded by national and international funding organisation and lead by staff from MfN have been carried out or are currently ongoing. The MfN is very well connected in the international community on impact and meteorite research and experts in this field are visiting the MfN frequently.

MfN is partner of ESA's Hera mission and the Horizon2020 project NEO-MAPP, which both focus on the study of the kinetic impactor technique to deflect asteroid trajectories. In the frame of these projects, impact simulations are conducted to study the momentum enhancement of the impact event, which is key to change an asteroid's trajectory. Further, the analysis of crater morphology or seismic signals enhances our understanding of the material characteristics of asteroids.

MfN developed the NEO Impact Effects Knowledgebase (SSA-P3-NEO-VIII) as contractor for ESA and is currently involved in the development of an operative tool to predict the ground effects of an Earth-asteroid encounter.

In addition, MfN was leading several research projects funded by the German Research Foundation (DFG) to gain a better understanding of impact processes, shock waves, and crater formation by numerical modelling and experiments.

INTRODUCTION INSTITUTE OF SPACE SYSTEMS - UNIVERSITY OF STUTTGART (IRS)

The plasma wind tunnel and electric propulsion system (PWK-ERA) working group of the Institute of Space Systems University of Stuttgart (IRS) has diverse heritage on spacecraft end of life servicing, demise characterization, use of electric propulsion system for reaching the moon as well as the utilization of lunar resources.

Studies of end-of-life servicing to deorbit medium [1] and small satellites of constellations [2] with the aid of thermal arcjets have been performed. The first case was part of the ESA Clean Space Initiative 2016 with the CleanSat BB28.

IRS has access to plasma wind tunnel facilities capable to produce high-enthalpy airflow conditions relevant for atmospheric re-entries. These facilities have been utilized to assess the demisability of spacecraft-relevant materials [3] as well as common Composite Overwrapped Pressure Vessel materials [4] as part of the ESA TRP "Characteristics of Demisable Materials". Additionally, investigations on biomaterials developed during ESAs GSTP Bio-composite Structure in Space Applications have been performed in plasma wind tunnel facilities. These activities are flanked by ESA projects making use of the gained material data base in order to improve existing model tools such as SCARAB (in cooperation with HTG and ESA) [5]. The gathered experience makes, in addition, significant contributions to the aerothermodynamic instrumentation aboard of the CubeSat SOURCE where an in-situ assessment of its uncontrolled re-entry is planned [6].

In parallel the investigation of in-orbit rendezvous technologies for non-cooperative targets (capturing) has been conducted in cooperation with the University of Cape Town, where a grabbing mechanism based on shape memory alloy was developed. For qualification of the mechanism and design iteration vacuum chambers of IRS have been utilized. [8, 9]

With various student theses system studies on electric propulsion systems for reaching the moon [10], landing and utilizing lunar resources have been performed [11, 12]. In each scenario the utilisation of in-situ resources (especially oxygen extracted from minerals) have been considered and respective facilities and systems have been conceptually designed [13].

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INTRODUCTION CASTELGRANDE OBSERVATORY

ISON-CASTELGRANDE OBSERVATORY

International Optical Scientific Network (ISON), being one of the largest systems of its kind in the world, has a long-standing history in observations of satellites and space debris as well as of *Near-Earth Objects* (NEOs) which resulted in deep knowledge in observational techniques and analysis of high quality. ISON is coordinated by the *Keldysh Institute of Applied Mathematics of Russian Academy of Sciences* (KIAM RAS) in Moscow and provides permanent monitoring of the entire geostationary orbit region. The entire network consists of 53 telescopes at 24 observatories, and the ISON-Castelgrande Observatory is one of them. It is located in a rural area at 1250 meters altitude ~7 km to the north-east from the Castelgrande commune within the province of Potenza of the South Italian region Basilicata (Figure 68). It shares the same mountain area with the Italian astronomical observatory run by Instituto *Nazionale di Astrofisica* (INAF, *Osservatorio Astronomico di Capodimonte* in Naples) with a 154 cm optical telescope TT1, one of the largest in continental Italy.

Figure 68: Location of Castelgrande in Italy.

CASTELGAUSS PROJECT

Upon the observatory installation in December 2014, the regular work at the ISON-Castelgrande Observatory (Figure 69) had been started in September 2017 as CastelGAUSS Project, which is a collaboration of GAUSS Srl (*Group of Astrodynamics for the Use of Space Systems*), of the Castelgrande municipality and of KIAM RAS. GAUSS Srl is an Italian private company in Rome specialized in the development and launch of small satellites, CubeSats and PocketQubes. First routine astrometric observations at the observatory began on October 26, 2017; regular photometric observations started in February 2019.

Figure 69: View of the ISON-Castelgrande Observatory (top, front) with its 2-m and 3-m domes together, and of the 22-cm telescope (bottom) of the observatory.

Throughout the last years the number and spatial distribution of space debris had been permanently and substantially increasing, giving a great potential collision threat for active satellites which would lead to their destruction on the one hand,

and to the snow-ball effect in space debris population growth on the other hand. Hence, to tackle this continuously growing problem the objective of the CastelGAUSS Project is to study characteristics of satellites, space debris and NEOs, such as rotation period, size, shape and surface composition, and positional measurements of GEO satellites for orbit determination and conjunction analysis. On the basis of the entire ISON observational work GAUSS and KIAM would offer satellite operators a contract service to provide positional measurements and orbital solutions of high accuracy.

OBSERVATORY QUALITY

The natural environment at the ISON-Castelgrande Observatory is perfectly suitable for qualitative astronomical observations in general and for observations of satellites and space debris in particular. The climate is a mixture of Mediterranean climate types *Csa* and *Csb*, which primarily means a small amount of precipitation, especially in summer. The local sky darkness had been measured with an SQM-L at multiple occasions; the best value so far was 21.47 mag/arcsec^2, and the average value on cloud- and moonless nights was 21.0–21.3 mag/arcsec^2, this corresponds to the class 3 on the Bortle sky quality scale. The average value of seeing was found to be 1.2 arcseconds. There is a substantial number of clear nights acceptable for observations; the best observing run so far was in April, July, and August 2018 with 20 observational nights, and even in winter, which is rather believed to be the worst season, there were 17 observational nights in January 2018; it total, the least average number is expected to be 15 nights per month or 180–200 nights per year. The local horizon is entirely open in almost all azimuth directions, so that observations of satellites and space debris are possible even at altitudes down to 1–2 degrees above horizon (Figure 70), thus, making the total view angle of ~175 degrees possible.

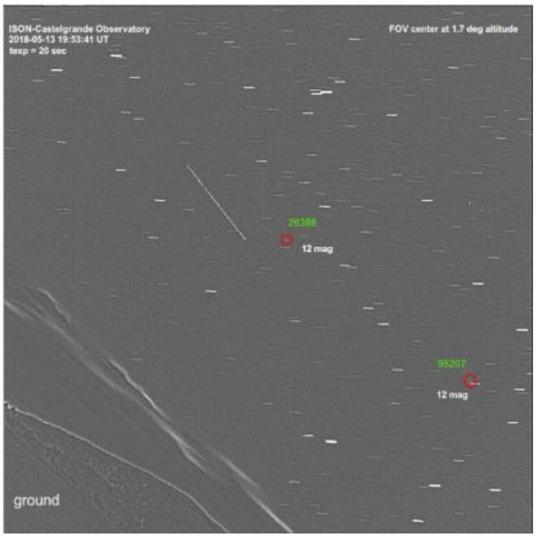


Figure 70: An image of satellite observation at 1.7 degrees above horizon; satellites with brightness of 12 magnitudes are clearly visible in the image.

The only natural disadvantages include the possibility of very strong winds and high humidity throughout the year, as well as deep snow and frost during the period from December till March; in the case of a heavy snowstorm the observatory area might become practically inaccessible for a couple of weeks.

To assist constant control of sky conditions, AAG CloudWatcher Solo sensors for clouds (sky temperature), precipitation, wind speed and air temperature are mounted on the observatory building's south wall. Prior to any observation the CCD camera is electrically cooled down to -20°C in summer or -25°C in winter to obtain noise-free images. The air-dehumidifier inside the dome automatically starts air-drying if relative air humidity reaches 85% or higher. Finally, the selected types of the telescope and the CCD camera yield a relatively large field of view of 4×4 degrees which allows to observe large sky fields.

CURRENT UPPER STAGE ROTATION PERIODS

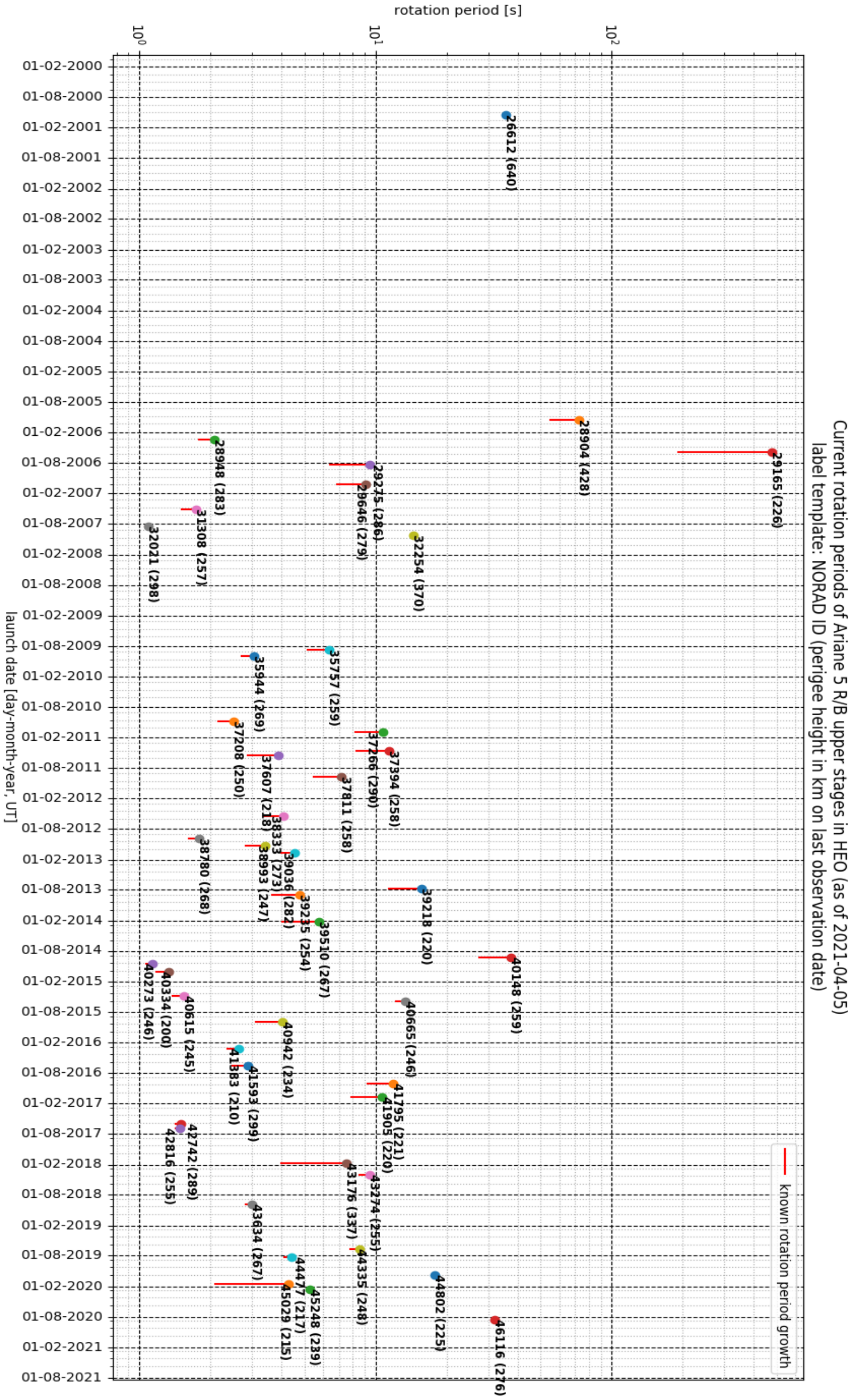
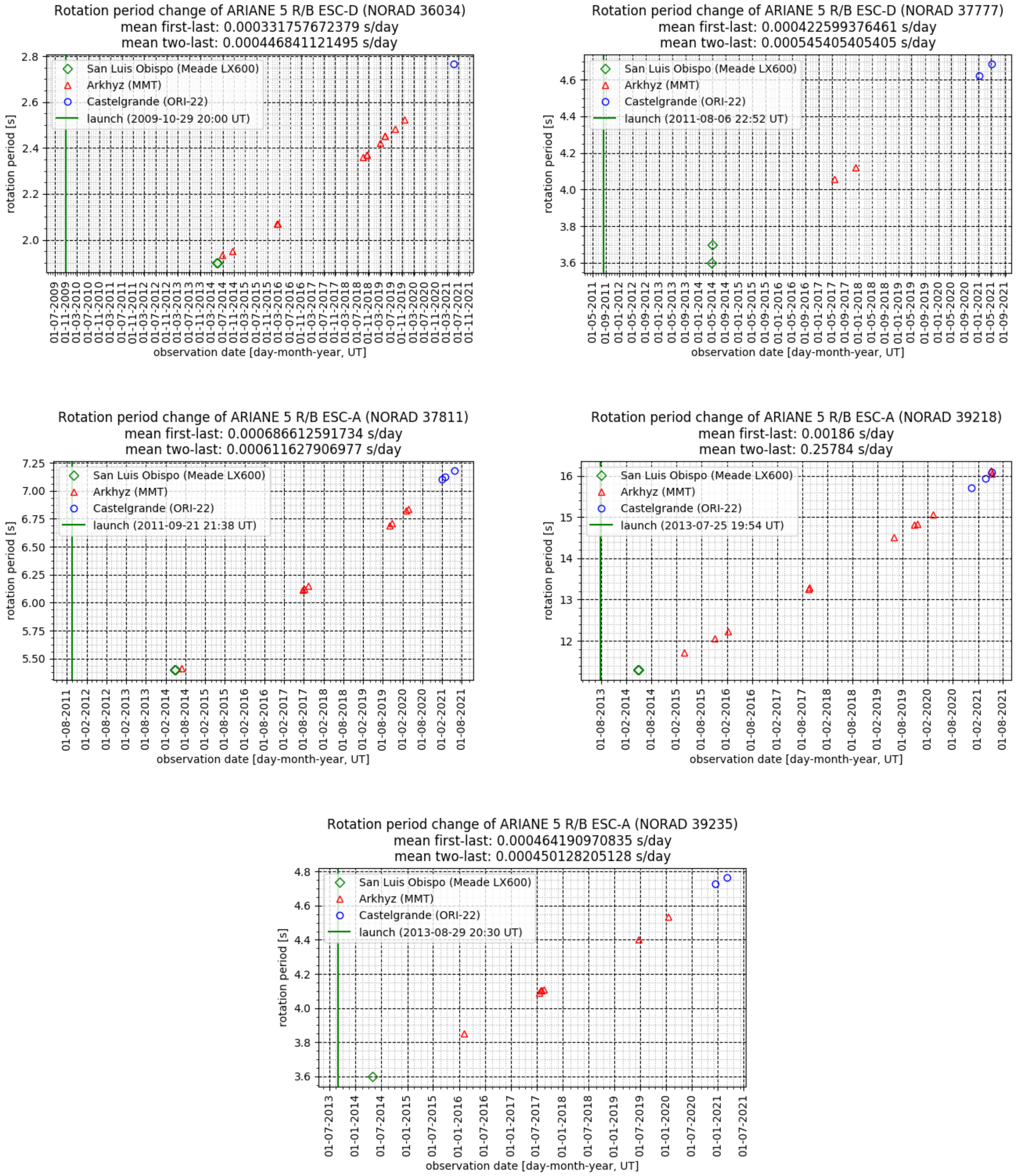


Figure 71: Current upper stage rotation periods (Schmalz, Castelgrande)

EXAMPLES OF THE NATURAL GROWTH OF UPPER STAGE ROTATION PERIOD



Further examples from Castelgrande Observatory et. al. showing the natural growth of the rotation period of Ariane 5 upper stages in GTO.

INTRODUCTION FRAUNHOFER FHR AND THE TIRA SYSTEM

THE FRAUNHOFER-GESELLSCHAFT AND FRAUNHOFER FHR

The Fraunhofer-Gesellschaft, as the world's leading applied research organization, focuses on developing key technologies that are vital for the future and enabling the commercial exploitation of this work by business and industry. Its research efforts are geared entirely to people's needs: health, security, communication, energy, and the environment. Founded in 1949, the Fraunhofer Gesellschaft currently operates 75 institutes and research institutions throughout Germany with the majority of the organization's 29.000 employees being qualified scientists and engineers. As a pioneer and catalyst for ground-breaking developments and scientific excellence, Fraunhofer helps in shaping society now and in the future.

The Fraunhofer Institute for High Frequency Physics and Radar Techniques (FHR) located near Bonn, Germany, is one of the leading and largest European research institutes in the area of high frequency physics and radar techniques. Fraunhofer FHR develops customized concepts, methods, and systems for electromagnetic sensors, particularly in the field of radar, together with innovative signal processing methods and state-of-the-art technology in the microwave to the lower terahertz frequency range. On one hand, the processes and systems developed at Fraunhofer FHR are used for research of new technology and design. On the other hand, together with companies, authorities, and other public entities, the institute develops prototypes to tackle unsolved challenges. The special focus here is on the maturity of the systems and their suitability for serial production to ensure a quick transformation into a finished product in cooperation with a partner.

RADAR FOR SPACE OBSERVATION: THE TRACKING AND IMAGING RADAR

Over the recent years the population of Earth-orbiting satellites as well as space debris has become increasingly dense. The latter poses a significant risk to active satellites and the multitude of applications, such as telecommunications, navigation etc. which depend upon them. Furthermore, the recent technological trend of active debris removal and/or recycling is projected to gain a substantial boost in the near future, thereby providing significant incentives and gains as a scientific and business field. For such efforts to be successful targeted studies of candidate objects are extremely important. The availability of accurate orbital parameters, as well as the knowledge of the in-orbit status and attitude of cooperative and non-cooperative space objects are mission critical parameters.

Within Fraunhofer FHR, the department Radar for Space Observation focuses on the development of innovative methods and technologies for the detection, tracking and imaging of space objects – from active satellites to space debris. The Department operates the prominent space observation radar TIRA (Tracking and Imaging Radar), which is unique in Europe and provides valuable support for space situational awareness and, in particular, the reconnaissance of space objects.

TIRA utilizes a 34-m Cassegrain antenna weighing about 240 tons. The system comprises two radars, i.e., a coherent, narrowband pulse radar for tracking that operates at the L band (centre frequency 1.333 GHz), as well as a coherent broadband imaging radar operating at the Ku band (centre frequency 16.7 GHz). The former provides highly accurate orbital parameters and the latter high-resolution imaging of space objects. The tracking radar with a peak power of about 1.5 MW is sensitive enough to detect a 2-cm sphere at a range of 1000 km. Furthermore, the imaging radar, with transmitting power of up to 13 kW, provides high spatial resolution inverse synthetic aperture radar (ISAR) images of space objects.

TIRA is a pivotal experimental facility for the development, investigation, and application of radar techniques for the detection and observation of objects in space. The radar data as well as the in-house developed techniques are used to determine characteristics of such objects, for instance obtaining precise orbital elements, intrinsic motion, and rotation parameters, estimates of the orbital of orbital lifetime, as well as their shape and size. TIRA also provides valuable support for space missions, e.g., during the launch and early operations phase as well as status assessment and damage analyses for spacecraft and resident space objects.

The department Radar for Space Observation possesses many years of experience in the field of space debris highlighted by performing many space debris related ESA projects including beam park experiments as well as targeted studies of resident space objects. Within the framework of the proposed project, TIRA can contribute with the observation and characterization of spent Ariane upper stages in geostationary transfer orbit, as has been demonstrated in a previous study [1].

The outstanding capabilities of TIRA together with the core competencies of Fraunhofer FHR are uniquely geared towards safety and sustainability in space.

Figure 72: TIRA (Image credit: Fraunhofer FHR)

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INTRODUCTION WARR E.V.

WARR EXPLORATION

The “Scientific Workgroup for Rocketry and Spaceflight” (German: *“Wissenschaftliche Arbeitsgemeinschaft für Raketentechnik und Raumfahrt”*), or “*WARR*” for short, was founded in 1962. The aim of this workgroup is to offer students the opportunity to supplement the theoretical knowledge they have acquired during their studies with practical experience, thus enabling students to enter professional life more easily. Currently, our project group Exploration consists of about 45 motivated students from the Technical University of Munich, all studying fields as varied as computer science, robotics, mechanical engineering, electrical engineering, physics, business administration, and management.

In the winter semester 2019/2020, we decided to refocus our project. The renewed interest in returning to the Moon, both from the political and scientific communities, has inspired us to contribute to its implementation. We are thrilled to assist in pushing the human space settlement frontier beyond the confines of the ISS. Our long-term goal is to produce a modular rover for the ESA Moon Village [1], which will enable a sustainable human presence on the Moon. A first step towards this will be a proof-of-concept design for the construction of a base on the lunar surface. In this process, the required structures will be fabricated using only regolith available on the Moon, which will be appropriately shaped using the technique of direct solar sintering. In addition, the modular design of the rover should enable additional applications, such as use as a test platform for various technologies as well as scientific research.

ROVER DESIGN

Our rover is designed to be a mobile construction machine. Thanks to the mounted direct solar sintering device, we can sinter regolith, a material found everywhere on the lunar surface. Such an In-Situ-Resource Utilization (ISRU) process enables us to establish a sustainable building procedure, in which building materials would not need to be brought from earth. Transportation costs associated with the mission would thus be significantly decreased.

The immediate goal of the project is to combine already proven solar sintering [2, 3] with a mobile rover platform. This should showcase the feasibility of such a system. The rover uses a standard 6-wheeled rocker-bogie drive system design. On the rover’s chassis, the payload is mounted using a horizontal 2-axis gantry as the interface. This allows for planar movement in two orthogonal directions of the large Fresnel lens. Focused sunlight from the Fresnel lens can therefore be moved along the sintering plane.

As the final step towards the IGLUNA[252] field campaign, we have recently passed the Readiness Review for the proof of concept in June 2021. Also, first tests on the sintering process have been successfully performed.

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[252] IGLUNA - space-innovation

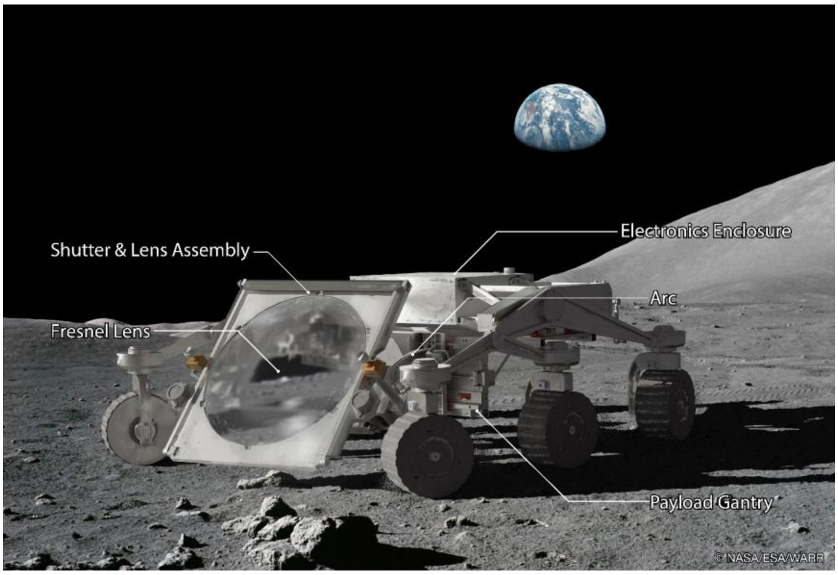

Figure 73: Major components of the solar sintering rover (©NASA/ESA/WARR)

PARTNERSHIPS

The Exploration project collaborates with Orbit Recycling GmbH on the topic of solar regolith sintering. We are working on integrating a rover platform with a direct solar sintering payload for demonstration and operational test purposes. We are using a quartz sand - soda (Sodium Carbonate) mixture for sintering in our operational tests and the IGLUNA 2021 Field Campaign to be able to simplify the process for demonstration. We plan to start using lunar regolith simulants in subsequent iterations. Therefore, the collaboration with Orbit recycling grants us access to their expertise on regolith simulant sintering and a partner for discussion of testing results.

With the participation at the ESA Lab@CH initiative IGLUNA 2021 as project REBELS (*Rover for the Establishment of Bases and Encampments on the Lunar Surface*), we are taking the first step in this direction. This first iteration will have the ability to sinter one layer directly onto the surface which the rover is driving on.

Figure 74: Solar sintering rovers in the context of the moon village (©NASA/ESA/WARR)

IGLUNA AND THE FIELD CAMPAIGN

IGLUNA is an interdisciplinary platform where students from worldwide universities design and collaborate on innovative projects for the future of space exploration and the improvement of life on Earth.

During the project, university students apply their knowledge to solve a technical challenge, to sustain life in an extreme environment, increasing in parallel the maturity of technologies relevant to the space domain. A board of experts from space agencies, renowned international companies, and research institutions are mentoring the students throughout the year to consolidate the projects for the Field Campaign.

IGLUNA is part of the ESA Lab@ initiative[253] launched by ESA to create a hub for innovation between universities, research organizations and industry. Space Innovation coordinates the IGLUNA platform and leads the main systems engineering activities, coaches the student teams, organizes the events, and communicates to the general public. More than 500 students from 13 countries have already taken part in one or several IGLUNA editions.

OUTLOOK

During the IGLUNA field campaign in July, we plan to evaluate our system at the summit of Mt. Pilatus. Over the 10-day period, we will analyze the performance of our system and the quality of the sintered samples. Based on the system behavior and data analyses, we will plan the next steps of our project in detail.

Currently, the most logical next step for the project is to bring our created structures into the 3rd dimension. For future iterations of the rover, subsequent layer application systems will be investigated, as well as any modifications to the system to permit higher printable structures. Additionally, attempts to automate certain critical systems of the rover will be conducted, to allow for easier implementation in the context of legitimate space exploration.

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[253] The ESA Lab Initiative - ESA

INTRODUCTION PLANETARY TRANSPORTATION SYSTEMS GMBH

PTS | PLANETARY TRANSPORTATION SYSTEMS

About Us

PTS is a European private space company focussing on developing technologies and infrastructure in space to support space exploration for all of humankind, with its headquarters and laboratories located in Berlin, Germany.

Twelve years of experience in commercial space technology development with a focus on mechatronics, electronics and software solutions used for in-house developed lunar equipment as well as towards customers and partner initiatives for Earth Orbit and lunar applications.

Winner of two Google Lunar XPRIZE Milestone Prize Awards for the development, maturation and qualification of the PTS space grade optics, brushless drives, motor controllers and on-board computer in cooperation with the German Aerospace Center (DLR).

Facilitator of the European commercial 'Mission to the Moon' campaign and supporting partner of the ArianeGroup 'Highway to the Moon'.

Close relationship and support from Zeitfracht Group, a logistics, airline, shipping and truck fleet operator, providing further economic stability and management experience.

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INTRODUCTION MOMENTUS

(Please see separate Momentus brochure)

Momentus is a first mover in offering in-space infrastructure servicesε and we believe that we will be vital to building out the tools, infrastructure, and services that will be instrumental to enabling the commercialization of space. Momentus will utilize a multi-pronged approach to provide three critical functions in the new space economy: Space Transportation, Satellite as a Service, and In-Orbit Services.

Momentus is planning to create the first hub and spoke model in space by offering last-mile delivery in partnership with leading providers of launch services on large and mid-size rockets. By combining the capabilities of low-cost launch vehicles from third party providers with our in-space transfer and service vehicles powered by water plasma propulsion technology, we expect to offer our customers significantly more affordable access to space. Our vehicles will be equipped with our in-house designed ground-breaking water plasma propulsion technology. We believe that this technology will enable us to deliver fast, versatile, and cost-effective services to our clients. We are confident that our highly experienced team of entrepreneurs, engineers, and operations managers will position us to be a market leader in the development of the new space economy.

Since our founding in 2017, we have successfully tested our water plasma propulsion technology in space, signed contracts worth approximately $86 million (as of March 4, 2021) in potential revenue, and have continued to develop and enhance our technology and vehicles. Our first launch with customers is anticipated to occur in June 2021. Our services are made possible by the rapid technological developments in the space industry over the past two decades, driven predominantly by significant decreases in launch costs, as well as the advent of smaller, lower-cost satellites. This convergence of trends has resulted in substantial growth in the commercial space market, rooted in higher accessibility for companies entering the new space economy that aim to offer communication, earth observation, and data collection services, and other satellite services.

We anticipate the space transportation and small satellite market to be drivers of growth in the short-term as satellite technology drives smaller and cheaper satellites and increasing numbers of satellite constellations continue to emerge. The total addressable market opportunity (“TAM”) for in-space transportation services for small satellites (up to 750 kg) to LEO is estimated to be $1.5 billion, and the TAM for customer payloads of up to 4,000 kg is estimated to be $10 billion and customer payloads of up to 20,000 kg is estimated to be $37 billion.

We believe that over the next decade, emerging new business models of space-based services, such as the generation of solar energy in space, space manufacturing, space data processing, and others will increase. These new business models could substantially increase demand for space transportation and other space infrastructure services. We are designing our vehicles to be compatible with most launch vehicles to maximize flexibility and competition within our supply chain. Pairing this competitive advantage with our competitive pricing, transportation efficiency, and our partnerships, we believe that we will play a key role in driving the industrialization and commercialization of space.

SUMMARY THESES AND CONCLUSION PART 1

SUMMARY OF THESES PART 1

T-SD-1	Space debris endangers all space activities due to uncontrollable collision risks.
T-SD-2	The amount of space debris is growing.
T-SD-3	Funding of ADR missions remain challenging.
T-RE-1	Recycling is driven by political decisions or financial benefits.
T-RE-2	Recycling can be separated in life cycle extension, reuse of components or material recycling.
T-RE-3	Terrestrial Recycling works best for certain raw materials like metal.
T-LCE-1	Life Cycle Extension (LCE) is proven in space.
T-LCE-2	Costs for LCE competes with costs for “*space object replacement*” (object successor)
T-RoC-1	Reuse of Components (RoC) is hardly proven in space.
T-RoC-2	Costs for RoC competes with costs for “*space object replacement*” (object successor)
T-RMR-1	Raw Material Recycling (RMR) is commodity on Earth but new to space. Still, RMR seems to be realistic for certain space scenarios like metal (aluminium) recycling, especially on the Moon.
T-RMR-2	Costs for RMR competes with costs from Earth materials or with local material alternatives (ISRU).
T-LA-1	Neither the UN space treaties nor the most recent space law provisions address the space debris problem.

Table 16: Theses Summary Part 1

SUMMARY OF CONCLUSIONS PART 1

C-SD-1	Like on Earth, Active Debris Removal (ADR) is needed to reduce or to stabilize the amount of space debris.	T-SD-1 T-SD-2
C-SD-2	Like on Earth, recycling might be a financing option for waste treatment in space.	T-SD-3
C-SD-3	Like on Earth, a better understanding of the debris composition is needed to allow ADR missions as well as recycling of space debris.	C-SD-1 C-SD-2
C-RE-1	Like on Earth, the right political decisions could boost a sustainable space recycling industry.	T-RE-1
C-RE-2	Like on Earth, due to technical limitations, recycling is not the answer for every kind of debris.	T-RE-2 T-RE-3
C-LCE-1	Life Cycle Extension (LCE) needs to be included already in the design phase.	T-LCE-1
C-LCE-2	Without standardization, LCE is financially not attractive as no scaling effects could be realized.	T-LCE-1 T-LCE-2
C-LCE-3	LCE in space is mostly interesting for objects with high launch costs, like heavier objects or objects in higher orbits (GEO)	T-LCE-1 T-LCE-2
C-RoC-1	Reuse of Components (RoC) needs to be included already in the design phase.	T-RoC-1
C-RoC-2	Without standardization, RoC is financially not attractive as no scaling effects could be realized.	T-RoC-1 T-RoC-2
C-RoC-3	RoC in space might be interesting for components with high launch costs, like large antennas or optics or for higher orbits (GEO). Still, hardly any financially attractive use case could be identified.	T-RoC-1 T-RoC-2
C-RMR-1	Terrestrial Raw Material Recycling (RMR) process technology is mature and proven and could be applied to space with minor adjustments.	T-RMR-1
C-RMR-2	Metal, especially aluminium, seems to be the “sweet spot” for RMR.	T-RMR-1
C-RMR-3	RMR works best for larger objects and objects with a high metal content.	T-RMR-1 T-RMR-2
C-RMR-4	RMR has the highest ROI of all identified recycling use cases.	T-RMR-2
C-RMR-5	The Moon is the financially most attractive recycling spot due to the upcoming metal demand for constructions of the planned Moon station.	T-RMR-2
C-LA-1	A legislation like the law of salvage under maritime law could be a solution to allow active debris removal from another country.	T-LA-1

Table 17: Conclusion Summary Part 1

SUMMARY RECOMMENDED NEXT STEPS PART 1

- Space debris should be officially considered as another (important) space resource, which should be researched at the *European Space Resources Innovation Centre* (ESRIC).
- Compared to Earth, the ownership or authority of a space object, functional or debris, does not terminate. Therefore, any space servicing operation incl. space debris recycling would not be possible without the explicit agreement of the registered owner of such an object. A legal base to handle these activities needs to be developed. ESA should continue its support and funding of the *European Centre for Space Law* (ECSL) and should encourage ECSL to focus further on the topic to provide a solid legal base for future activities from Europe in this area.
- Official space debris data sets like DISCOS should be extended with object material information to support future waste management activities. On Earth, this missing information hinders efficient treatment of old landfills. In space, similar problems will occur when debris will be addressed in the future. Ideally, this is done as part of or as an extension of the currently rebuilt of ESA`s LCA data set.
- Life cycle extension in space is a proven way to address the common “throwaway” mentality of space missions. Low hanging fruits for life cycle extensions could be docking plates or refuelling concepts, while mid-term, replaceable external components like antennas and solar panels should be standardized. Long-term, internal component replacements, of e.g., batteries or *Guidance, Navigation & Control Systems* (GNC) should follow. ESA should support this sustainable development by including it in its own tender for future space missions.
- The recommendations for reusing components in space are like the life cycle extension scenario. But even with the help of future standards, a valid business case for LEO is hard to imagine due to the decreasing satellite and launch costs. In higher orbits, such a business case could be developed over time with the increasing number of standardized satellite interfaces. Being (at least partly) responsible for the large European satellite fleet of the *Copernicus* and *Galileo* service, ESA should request the mentioned capabilities for its own next satellite generations and could act as a best practice for life cycle extension.
- As raw material recycling from space debris is within Europe`s technology capabilities, ESA should consider the usage of recycled material for future space manufacturing activities, especially on the Moon. Even if the material would not come from orbital space debris at the beginning, lunar lander or rover material could be recycled after their missions to reduce or avoid additional material transports from Earth. These end-of-life recycling aspects should be included in future mission profiles.
- Without a clear political commitment, the recycling activities for space debris will remain a challenge, regardless of any potential economic benefit. While *ClearSpace-1* is a first step in the right direction, the funding of following ADR missions remains unclear. With the financial benefits of a space debris recycling concept, a successful *ClearSpace-1* mission might unlock additional public budgets for future ADR missions, if prepared well enough in advance. If ESA sees advantages in such activities, this topic (space debris recycling) should be included on the agenda of ESA`s next Council at Ministerial Level.

SUMMARY RECOMMENDED NEXT STEPS PART 2

- The selection criteria to identify space debris targets for recycling could be further improved through the following activities:
    1. The data regarding space object composition is limited but crucial for future recycling activities. Efforts should be considered to extend the existing debris data sets like DISCOS with detailed material information, ideally provided by the manufacturers. This such be considered for the next update project for DISCOS.
    2. GTO upper stages cross many other object trajectories. Due to their sizes, any fragmentation event through explosions or collisions would generate a large amount of secondary space debris objects, which expose all other space objects to unpredictable risks. Like in the LEO environment, the associated risks for GTO debris objects should be reviewed and modelled in more details as part of a dedicated research study.
- The rotation and tumbling behaviour of upper stages in GTO should be understood in more details, as this would simplify any upcoming recycling mission. For this, a European research activity is suggested as a dedicated follow-up to this study:
    1. The already and ongoing light curve measurements of the CastelGAUSS observatory and its partner network should be combined with the capabilities of the Fraunhofer FHR TIRA instrument. This would allow Europe to generate a unique data pool of different GTO data sources.
    2. The data should be used for object tumbling modelling by institutes like the *Astronomic Institute* of the University Bern (AIUB) around Professor Zimmerwald or the *Institute of Technical Physics* from DLR in Stuttgart. The derived tumbling rates could be further reviewed and improved through illuminated 3D models in an experimental setup.
    3. To validate the derived tumbling and rotation models, a precursor mission in GTO is proposed. A visual inspection of a derelict upper stage should occur, which would help to not only determine the exact tumbling and rotation movements of the upper stage, but to inspect and to observe any space aging effects of the upper stage material. Ideally, such a precursor mission is executed as a (university) research competition. By offering a free slot in one of the planned GTO rideshare launches, ESA could support this precursor mission concept with an affordable investment.
- Contactless detumbling methods are very promising solutions to stabilize any kind of space objects. It is suggested to conduct experiments and studies in Europe, driven by ESA, with different coil designs regarding diameter and conductor material to develop a generic tool to be used for various detumbling scenarios in the future.
- Europe has started its own active debris removal mission *ClearSpace-1* to grab an object in space. It is highly recommended to verify, that the developed solution could be scaled for larger targets like the Ariane 5 upper stages. This could be done as part of a dedicated industry study.
- The recycling space tug concept is still at an early development stage and additional research needs to be done.
    1. ESA should take the presented concepts as a baseline for a CDF engagement to find the optimal balance between the contradicting requirements of quickly approaching the target in GTO and the long Moon transfer.
    2. Synergies with existing activities should be identified, like the Vega-C Venus upper stage or the *Space Rider* propulsion technology, developments in GNC, AOCS or manipulators. Especially the *ClearSpace-1* mission should be followed closely to validate, that the developed technology components could be scaled for the larger recycling targets and tugs. This should be done as part of a dedicated cooperation office within ESA.

- To better understand the crater dependencies on the impact velocity and impact angle, additional studies and impact experiments should be carried out. The MfN in Berlin, Germany around Prof. Wünnemann as well as the Fraunhofer EMI Institute, Freiburg, are both perfectly suited for such activities and could execute such a study in partnership with Orbit Recycling.
- The presented early-stage concept to recover aluminium fragments of an impacted Ariane upper stage on the Moon should be re-examined at a time when more information about the Ariane 6 A64, EL3, and PHASR is available. A CDF is proposed like the space tug situation, where experts from ESA, Orbit Recycling as well as the European space industry should evaluate the synergies with other relevant developments in this area.
- The overall knowledge of aluminium casting in regolith mould is still limited. As part of a shared PHD with the EAC, further studies at TU Berlin and Orbit Recycling will occur over the next 3 years. In addition, aluminium smelting and casting experiments under vacuum conditions should be executed. These experiments should give a better understanding of the achievable cast quality on the Moon.
- The effectiveness of Fresnel-lens-based aluminium melting in regolith should be studied. Additional tests should validate the preliminary results under vacuum conditions, where cooling would only happen through heat radiation. This could be done as part of a shared PHD or a dedicated industry study of Orbit Recycling with the support of EAC or ESTEC laboratories.
- Additional Fresnel lens sintering experiments should occur with different regolith simulants as well as under vacuum conditions to validate the achievable mould quality. This could be executed by Orbit Recycling with technical support of ESTEC laboratories.
- Different Fresnel lens material should be evaluated for its usage under lunar conditions. This could be executed by Orbit Recycling with technical support of ESTEC laboratories.
- Rover with Fresnel lenses should be tested to determine the size of the achievable glazed surface areas per time unit for different lunar applications. This could be executed by Orbit Recycling and its Partner PTS, Berlin, and TU Berlin with technical support of EAC and ESTEC laboratories.
- By mixing aluminium (powder) with regolith, a new material composition (*ALReCo*) could be produced. First experiments show a superior heat conductivity and thermal capacity of this new material compared to pure regolith, which needs to be validated in dedicated experiments. As this material might be even suitable as a heat storage solution to power a lunar ground station, corresponding research should occur to validate these assumptions.
- The presented business case estimations are based on public information and assumptions. These numbers should be validated from Orbit Recycling and experts from various ESA directorates at a dedicated workshop, e.g., during a side meeting of an upcoming ESA conference.
- Beside the direct cost savings, space debris recycling has positive effects on the environment and reduces the overall risks through space debris. These positive effects should be validated in a dedicated *Life Cycle Assessment* (LCA).

DELTA-V CALCULATIONS FOR CHASER TUG

Chaser Space Tug scenario details:

- Chaser space tug dry weight: 500 kg
- Estimated delta-v per mission: 270 m/s, Isp: 220s.
- Total weight chaser space tug for scenario “12 missions”: 3,000 kg
- Total weight chaser space tug for scenario “8 missions”: 1,700 kg
- Rocket equation:[254] $M_{final} = M_{initial}\, e^{-\frac{270}{220s*9,80665}}$

Mission	M_{final} in kg	Calculated propellant in kg	Propellant with 15% margin	M_{final} with margin in kg
1	2647,1	352,9	405,8	2594,2
2	2289,0	305,2	350,9	2243,2
3	1979,4	263,9	303,5	1939,8
4	1711,6	228,2	262,4	1677,4
5	1480,1	197,3	226,9	1450,5
6	1279,8	170,6	196,2	1254,2
7	1106,7	147,5	169,7	1084,6
8	957,0	127,6	146,7	937,9
9	827,5	110,3	126,9	811,0
10	715,6	95,4	109,7	701,3
11	618,8	82,5	94,9	606,4
12	535,1	71,3	82,0	524,4

Table 18: Chaser Space Tug - 12 Missions Scenario

Mission	M_{final} in kg	Calculated propellant in kg	Propellant with 15% margin	M_{final} with margin in kg
1	1500,0	200,0	230,0	1470,0
2	1297,1	172,9	198,9	1271,2
3	1121,6	149,5	172,0	1099,2
4	969,9	129,3	148,7	950,5
5	838,7	111,8	128,6	821,9
6	725,2	96,7	111,2	710,7
7	627,1	83,6	96,1	614,6
8	542,3	72,3	83,1	531,4

Table 19: Chaser Space Tug - 8 Missions Scenario

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[254] E.g., Biesbroeck: Lunar and Interplanetary Trajectories, Springer Praxis Books, 2016

RETROREFLECTORS AND MARKERS

Laser Retro-Reflectors (LRR) are perfectly suited for far range operations. LRR consists of an array of cubes mounted on a hemispherical frame. They are designed to reflect light back in precisely the same direction it originates to allow independent measurements of the object's position. According to previous experience, it is possible to model the attitude of small tumbling satellites in LEO using several "*corner cubes*" distributed on a satellite's face[255]. As part of the activities for the CHAMP[256] mission, the *German Research Centre for Geoscience* (GFZ) Potsdam decided to equip this small satellite with a *Laser Retro Reflector* (LRR) of novel design with at least centimetre resolution.

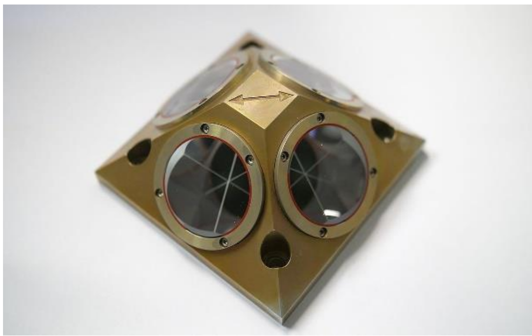

Figure 75: LASER Retro-Reflector for CHAMP (Bauer, GFZ)

The Laser Retro Reflector (LRR) onboard a spacecraft for a *Global Navigation Satellite System* (GNSS) must be designed differently. Due to the large distance of GNSS satellites to the laser ground stations (> 19,000 km), the return signal strength is weak. The disadvantages of a LEO LRR can be overcome by the use of a single element hollow reflector which is presently investigated in cooperation between GFZ Potsdam and SpaceTech GmbH Immenstaad. Due to the much larger aperture compared to a conventional quartz prism, the far field diffraction pattern for this reflector is much sharper and the return signal of a single large hollow reflector is said to be 2 – 4 times stronger than for a conventional LRR[257].

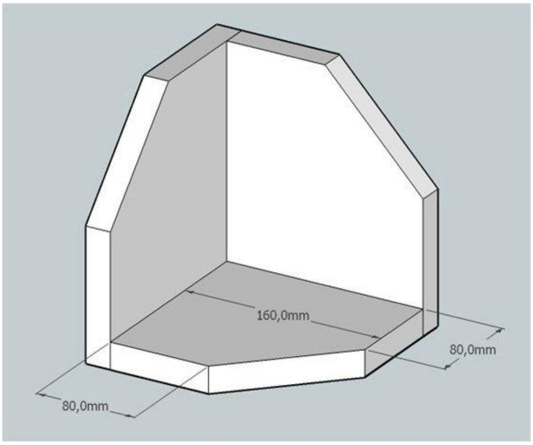

Figure 76: Proposed design of hollow reflector for GNSS (GFZ)

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[255] Determination of Attitude and Attitude Motion of Space Debris

[256] CHAMP - CHAllenging Minisatellite Payload - GFZ

[257] Hollow Reflector for GNSS Satellites - GFZ

For approaching objects in space, different technology is used. Such an approach, called rendezvous, is extremely complex and has to deal with illumination conditions, that can change very quickly and often in orbit. One solution to make the rendezvous phase achievable is to embed markers on the target that could support relative navigation between the chaser and the object. The objective of these markers is to provide information on the range between the chaser and the target. They should also enable "*pose estimation*" of the target, which can be used to characterize its tumbling movement. Finally, they will also provide a reference target for the chaser to aim at.

Instead of having one big marker with a characteristic pattern to determine the target's attitude, locating multiple smaller markers on several sides of the spacecraft allows to draw unique patterns, so that it is possible to identify the side and thus reconstruct the attitude of the target. As the chaser gets closer to the target, there is a point from which the chaser can no longer observe the full target due of field of view limitations. When this point is reached, relative navigation can no longer rely on 2D markers. Instead, a single 3D marker is used, which must be located on the target side to be captured by the chaser. In fact, this marker would only be used for the final approach that leads to capture. The 3D marker requires an active illumination source on the chaser, in addition to a visual camera. The protrusion of the 3D marker, coupled with a painted pattern, gives different images depending on the relative position of the chaser.

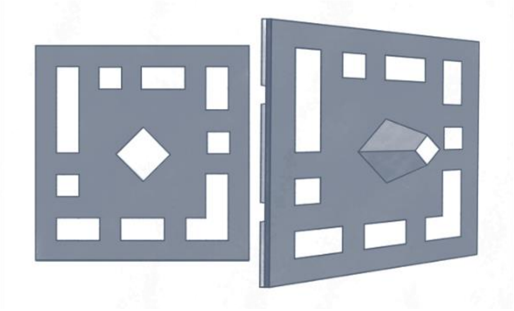

Figure 77: 3D marker example of approaching a target in space (ESA)

Ideally, LRR and marker are combined in such a way, that the visual pattern required for the marker is added to the sides of the hollow reflector. Alternatively, the pattern can be composed of elevated LRR over a visual pattern on the object, which is either hidden or visible to the chaser, depending on the relative position to the target. A simplified sketch of such a solution is presented below.

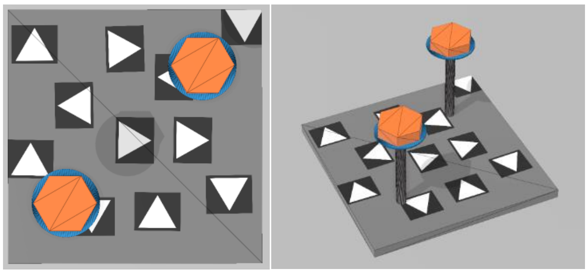

Figure 78: LRR (orange) and 3D marker (pattern); top and side view, simplified (Koch, Orbit Recycling)

Investigation of Ariane5 Upper Stages in GTO with the TIRA Space Observation Radar

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INTRODUCTION AND BACKGROUND

The rapidly increasing number of space debris necessitates viable approaches for a sustainable growth of the space industry. As a result, viable active debris removal (ADR) proposals are becoming essential and for their success, accurate, actionable, and easily obtainable data on potential targets are of utmost importance.

Spent rocket bodies in geostationary transfer orbit (GTO) may constitute targets for future ADR missions. They are often rotators characterized by short periods, below 25 s, as derived by optical observations (e.g., Silha et al., 2020). The apparent rotation period is a combination of the satellite's intrinsic rotation and its orbital motion. In the following, the orbital motion is assumed much slower than the intrinsic rotation and all reported periods are apparent.

The space observation radar TIRA of Fraunhofer FHR can contribute with observations and characterization of spent Ariane upper stages in geostationary transfer orbit (GTO), as has been demonstrated in previous studies (e.g., Leushacke, 1993). In the context of the present study, targeted specifically at ADR, a small sample of spent Ariane 5 upper stages in GTO was observed with TIRA with the aim of characterizing their rotational status. These constitute precursor observations to a potential future dedicated observation and characterization campaign aimed at meaningful sub-samples of interesting targets in GTO. The objects targeted here were four ESC-A cryogenic upper stages utilized by the Ariane 5 launcher in its ECA version. The ESC-A cryogenic upper stage has dimension of 5.46 m, by 5.46 m, by 7.286 m, and a mass of about 5000 kg. The goal of these precursor observations and analysis was to prove the feasibility and scientific relevance of a larger scale study. The initial results obtained are promising and relevant for the support of future ADR missions. Further details, observational parameters and results are discussed in the following sections.

Object	NORAD ID	Intl. Designator	Date	Total Obs. Duration [s]	Min. Range [km]	Max. Range [km]
Ariane 5 R/B	29498	2006-043E	2021.03.08	3718.8	6158	20283
Ariane 5 R/B	38780	2012-051C	2021.03.09	4450.2	6467	23775
Ariane 5 R/B	43176	2018-012C	2021.03.12	1174.8	5589	9495
Ariane 5 R/B	28904	2005-046C	2021.05.10	2228.4	9541	17427

Table 1: Observational Parameters for the four Ariane 5 R/B in GTO.

THE VALUE OF RADAR DATA

Even with the proliferation of optical telescopes and surveys, the availability of long data sets on objects in GTO remains limited. Especially, in the context of projects such as the one at hand, additional information from detailed studies of sub-samples of Ariane 5 rocket bodies is crucial.

Radar techniques are ideally suited for targeted studies of resident space objects in GTO as radar observations come with a number of advantages that make them very competitive and sought-after. Owing to the frequency bands used by radar and its active nature as a sensor, radar observations can be performed at any time, under almost any weather conditions and are independent of target illumination conditions. Multiple targets can be observed during relatively short observing sessions. Radar systems offer high pulse repetition frequencies (PRF) leading to high-cadence observational data. For instance, the typical PRF for TIRA's tracking radar is 30 Hz. As a result, TIRA can easily gain insights into fast rotating space objects. Furthermore, long observations are easily attainable with radar. TIRA can achieve observation length of tens of minutes at a time, exploring samples of very slow rotators too. Obtained data are of high fidelity with small instrumental errors and free of certain biases that optical data may be affected by (e.g., coupling between measured magnitude and rotation period; see Sect. 2.6.7 by Silha et al., 2020, and references therein).

Combining the above advantages, radar can offer highly detailed and statistically robust studies of promising objects; for instance, objects (pre-)selected from optical surveys as well as for cross validation between optical and radar scientific results.

CHARACTERIZATION OF ARIANE5 R/B IN GTO WITH RADAR

In this precursor study, four observation of Ariane 5 upper stages in GTO were performed using the TIRA space observation radar between March and May 2021. The long ranges involved in observations of objects in GTO practically exclude direct imaging using the imaging radar of TIRA. As a result, all data were acquired using the tracking radar of TIRA operating at the L-band (center frequency of 1.333 GHz). All observations were performed with a nominal PRF of 30 Hz. Table 1 details the parameters for each observation.

The main observable, relevant to this study, is the radar cross section (RCS) and its temporal variation within the observation interval, i.e., the RCS signature of the target. The RCS plot shows the relative intensity of the backscattered radiation in decibels relative to one square meter (dBsm) as a function of time. As an example, Figure1 shows the temporal evolution of the RCS of Ariane 5 R/B (28904) during the observation on May 10, 2021. The rapid temporal variability of the RCS and the periodically repeating pattern therein indicate a relatively fast rotation of the object.

For the extraction of scientific results and characterization of the RCS signatures of the aforementioned targets a large suite of time series analysis and periodicity extraction methods were utilized, including a detailed autocorrelation and Fourier analysis (power-spectral-density, Lomb-Scargle periodogram etc.). The results indicate that three out of the four observed targets show, in addition to a slower component, also fast periodicity in their RCS signatures.

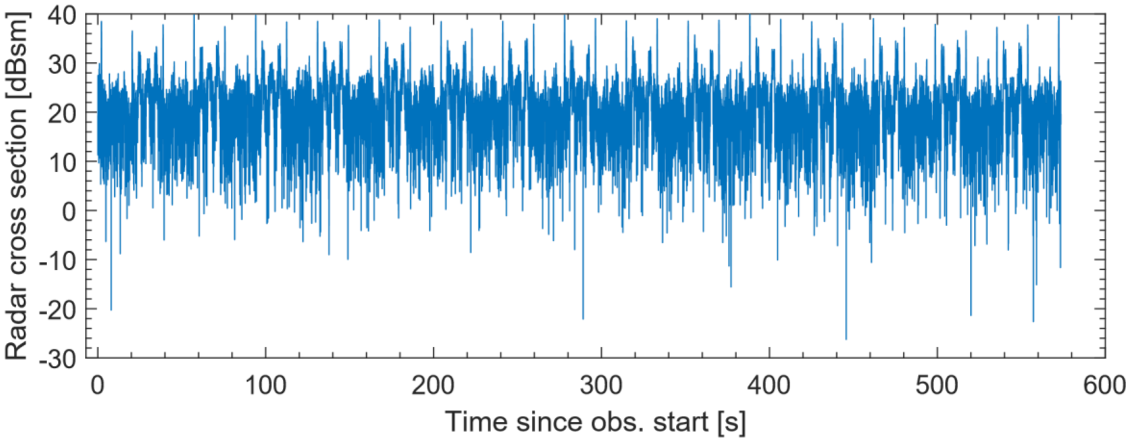

Figure 1: Temporal evolution of the RCS of Ariane 5 R/B (28904, 2005-046C) observed with TIRA's tracking radar on May 10, 2021. The sampling rate is 30 Hz and the length of the observation shown is 573.5 s.

Below, the findings for each individual case based on the time series analysis are presented in some detail.

Ariane5 R/B (29498): The observation of upper stage 29498 on March 8, 2021, was performed for 3718.8 s at ranges between 6158 km and 20283 km. The data indicated a complicated pattern with fast periodicity present in the RCS signature. Periods of the order of seconds were the dominant components in the RCS signature. Parts of the time series may hint at longer periods; the power, however, that can be associated with these is relatively low.

Ariane5 R/B (38780): The observation with TIRA of upper stage 38780 on March 9, 2021, spanned 4450.2 s at ranges between 6467 km and 23775 km. The data indicated fast periodicity present in the RCS signature. Periods of the order of seconds were the dominant components in the RCS signature. A slower modulation of the order of 30 s is also present, but this characterizes parts of the observation and the power associated with it is relatively low.

Ariane5 R/B (43176): This observation was performed on March 12, 2021, over a period of 1174.8 s from a minimum range of 5589 km up to a maximum range of 9495 km. Also, in the case of upper stage 43176, fast periodicity appears to dominate the RCS signature, with dominant periods from few seconds down to about 1 s. As in the case of Ariane 5 R/B (38780), a slower modulation may be present with a period of 18 s, characterizing parts – albeit longer compared to 38780 – of the observation. The power associated with the latter period is lower as the RCS signature is dominated by the high frequency (or short period) components.

Ariane5 R/B (28904): The situation for Ariane 5 upper stage 28904 appears somewhat different. This object was observed with TIRA on May 10, 2021, for 2228.4 s at ranges between 9541 km up to 17427 km. The RCS signature, shown in Fig. 1, indicates the presence of clear periodicity even by visual inspection. Once again, faster beating can also be seen in the signature. A significant fast component can be identified with a period of 4.6 s. A significant slower period, that characterizes the RCS in its entirety, is identified with a period of 36.8 s. The former may be associated with the small-scale distribution of radar scattering centers, while the latter, the slowest period in the signal, may well be associated with the large-scale apparent rotational period of the object.

SUMMARY AND FUTURE OUTLOOK

The salient results of this study can be summarized as follows:

Building on the existing experience of Fraunhofer FHR and utilizing the power of the space observation radar TIRA, this precursor study was initiated. The aim was to prove the feasibility and scientific relevance of a future dedicated observation and characterization campaign, targeting meaningful sub-samples of interesting targets in GTO.

In this framework, observations of four ESC-A cryogenic upper stages were performed with the tracking radar of TIRA. The objects (NORAD IDs: 29498, 38780, 43176, and 28904) were tracked for long time intervals – of the order of few thousand seconds, at ranges from few up to few ten thousand km, with high pulse repetition frequency, thus obtaining well-sampled RCS signatures for each one.

The subsequent periodicity analysis revealed that three out of the four observed targets, namely

Ariane 5 R/B 29498, 38780, and 43176, also show relatively fast periodicity in their RCS signatures. Periods of the order of seconds were the dominant components of their RCS signatures. Slower, but lower-power, periods characterizing parts of the respective observations are present.

The situation appears different for the fourth object, namely Ariane 5 R/B 28904. A significant fast component, with a period of 4.6 s, as well as a significant slower period of 36.8 s were identified. The latter characterized the RCS signature in its entirety and may well be associated with the large-scale apparent rotational period of the object.

This precursor study offered promising first results. The methods used here can be easily extended to larger samples of objects in GTO with the goal of detailed characterization. The relevance of such an extension is apparent and will become a necessity given the need for high-quality data, crucial to the success of any future ADR mission.

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HOW MUCH MONEY DOES SPACE-FARING FIRM SPACEX SAVE WHEN IT REUSES A FALCON 9 BOOSTER?

This week, CEO Elon Musk divulged some details about the economics of saving rockets, revealing why it makes sense in the long term.

SpaceX has gradually perfected the techniques that help it land a Falcon 9 booster after missions, moving from landing two boosters in 2014 to landing 15 boosters in 2017. Designing a rocket to land means it can carry less into space, as it requires leftover fuel for the return trip. SpaceX also needs to spend money on refurbishments.

This week, NASA Spaceflight reporter Michael Baylor explained on Twitter that United Launch Alliance, another player in the new space race, has claimed that a company needs to reuse a rocket 10 times for the economics to make sense. SpaceX, Baylor noted, is up to six landings with a single booster.

In response, Musk wrote:

"Payload reduction due to reusability of booster & fairing is <40% for F9 & recovery & refurb is <10%, so you're roughly even with 2 flights, definitely ahead with 3."

The comments shed some light on the finances behind reusing rockets, suggesting that the payload that can fly on a single rocket is reduced by less than 40 percent with a reusable configuration and that the cost of recovery and refurbishment makes up less than 10 percent of the initial production cost.

The concept makes sense on paper: If you can reuse a rocket, you're using resources more efficiently. Musk has compared it to flying single-use airplanes.

BUT THE ACTUAL COSTS HAVE REMAINED RELATIVELY OBSCURE. In 2013, at the *All-Things Digital conference* in California, Musk claimed that the first-stage booster makes up 75 percent of the overall price tag, reported at the time to be around $60 million, Space News reports. SpaceX's website lists the standard payment plan for a Falcon 9 launch at $62 million.

In 2018, ahead of a Falcon 9 Block 5 launch, Musk broke down the costs again. The boost stage, he stated, costs around 60 percent of the total costs, with the upper stage 20 percent, the fairing 10 percent, and the final 10 percent associated with the launch itself. This, CNBC noted, would instead place the cost of a booster at around $37 million.

The final price tag can vary, though. CNBC reported in April that the United States Air Force's launches were costing $95 million due to the extra security involved. SpaceX director of vehicle integration Christopher Couluris said during a briefing this year that reusing rockets can bring prices lower, adding that it "costs $28 million to launch it, that's with everything."

In terms of the marginal costs, the costs associated with producing just one extra rocket, Musk also recently shed some further light on the figures. In an interview with Aviation Week in May, Musk listed the marginal cost of a Falcon 9 at $15 million in the best case. He also listed the cost of refurbishing a booster at $1 million. This would fit with Musk's most recent claim that the costs of refurbishment make up less than 10 percent of the booster costs.

Assuming Musk's most recent claim is correct, the costs of reusing a booster come out ahead after three flights. How many flights could SpaceX do with a single booster? Musk, in response, claimed there was perhaps no limit:

"I don’t want be cavalier, but there isn’t an obvious limit. 100+ flights are possible. Some parts will need to be replaced or upgraded. Cleaning all 9 Merlin [Falcon 9 engine] turbines is difficult. Raptor [the engine for the upcoming Starship] is way easier in this regard, despite being a far more complex engine."

THE INVERSE ANALYSIS – SpaceX's rocket reusability program is a long-term investment, and it can be hard to quantify the overall savings due to the myriad of factors at play. Musk noted in March 2017 that the company had spent over $1 billion in reusable launch technologies, which meant the firm also needs to recoup the development costs from the reuse program rather than directly passing on those savings to the consumer.

But SpaceX's investment does not stop with the Falcon 9. The Starship, SpaceX's in-development rocket being produced in Texas, is designed to offer full reusability. As Musk noted, the ship's Raptor engine is much easier to reuse. If it holds up to its promise, that could make the question of whether it makes sense to fly a booster two or three times largely irrelevant.

Reusing a Falcon 9 could save money. landbysea/iStock Unreleased/Getty Images

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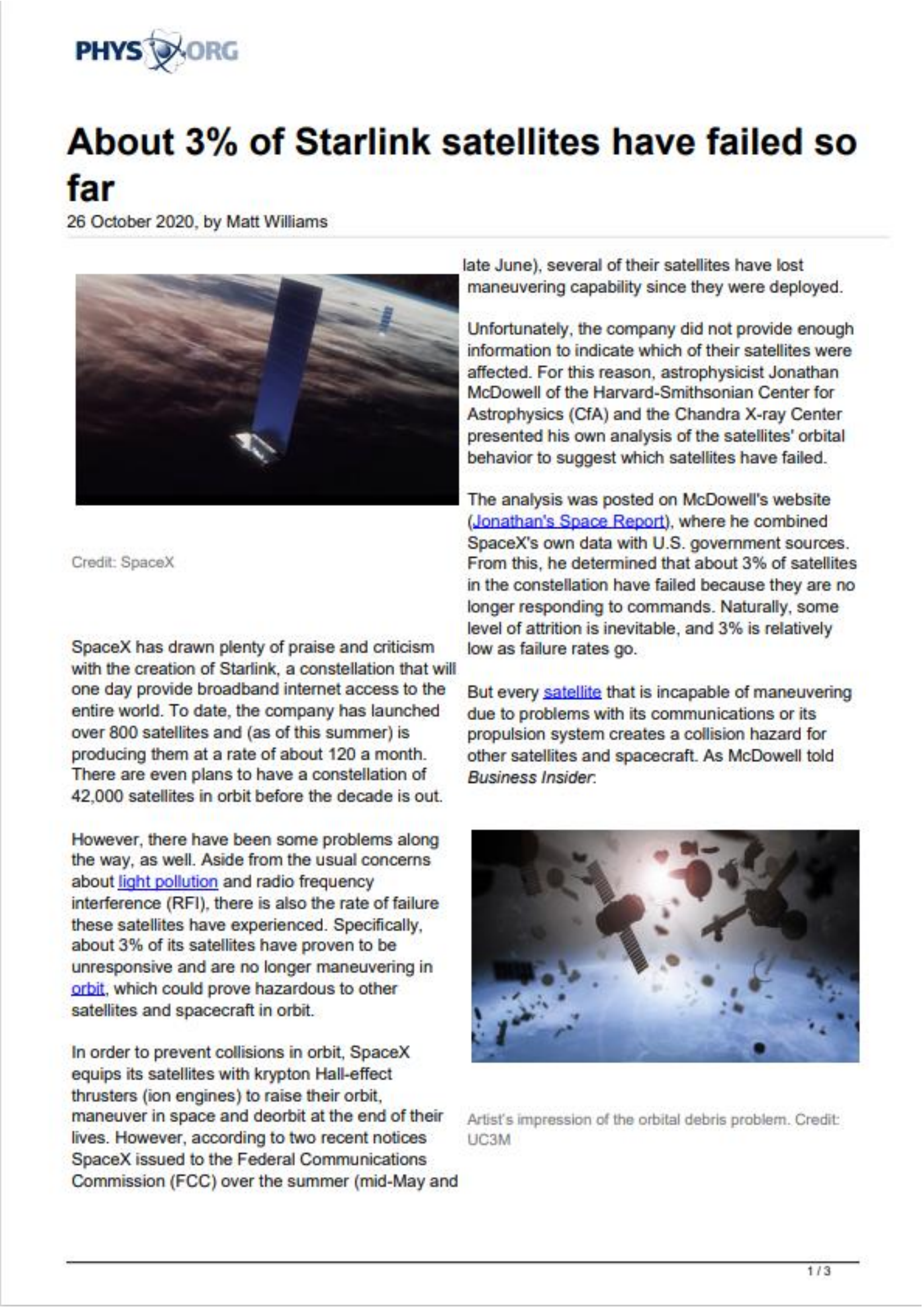

PHYS ORG

About 3% of Starlink satellites have failed so far

26 October 2020, by Matt Williams

Credit: SpaceX

SpaceX has drawn plenty of praise and criticism with the creation of Starlink, a constellation that will one day provide broadband internet access to the entire world. To date, the company has launched over 800 satellites and (as of this summer) is producing them at a rate of about 120 a month. There are even plans to have a constellation of 42,000 satellites in orbit before the decade is out.

However, there have been some problems along the way, as well. Aside from the usual concerns about light pollution and radio frequency interference (RFI), there is also the rate of failure these satellites have experienced. Specifically, about 3% of its satellites have proven to be unresponsive and are no longer maneuvering in orbit, which could prove hazardous to other satellites and spacecraft in orbit.

In order to prevent collisions in orbit, SpaceX equips its satellites with krypton Hall-effect thrusters (ion engines) to raise their orbit, maneuver in space and deorbit at the end of their lives. However, according to two recent notices SpaceX issued to the Federal Communications Commission (FCC) over the summer (mid-May and late June), several of their satellites have lost maneuvering capability since they were deployed.

Unfortunately, the company did not provide enough information to indicate which of their satellites were affected. For this reason, astrophysicist Jonathan McDowell of the Harvard-Smithsonian Center for Astrophysics (CfA) and the Chandra X-ray Center presented his own analysis of the satellites' orbital behavior to suggest which satellites have failed.

The analysis was posted on McDowell's website (Jonathan's Space Report), where he combined SpaceX's own data with U.S. government sources. From this, he determined that about 3% of satellites in the constellation have failed because they are no longer responding to commands. Naturally, some level of attrition is inevitable, and 3% is relatively low as failure rates go.

But every satellite that is incapable of maneuvering due to problems with its communications or its propulsion system creates a collision hazard for other satellites and spacecraft. As McDowell told *Business Insider*:

Artist's impression of the orbital debris problem. Credit: UC3M

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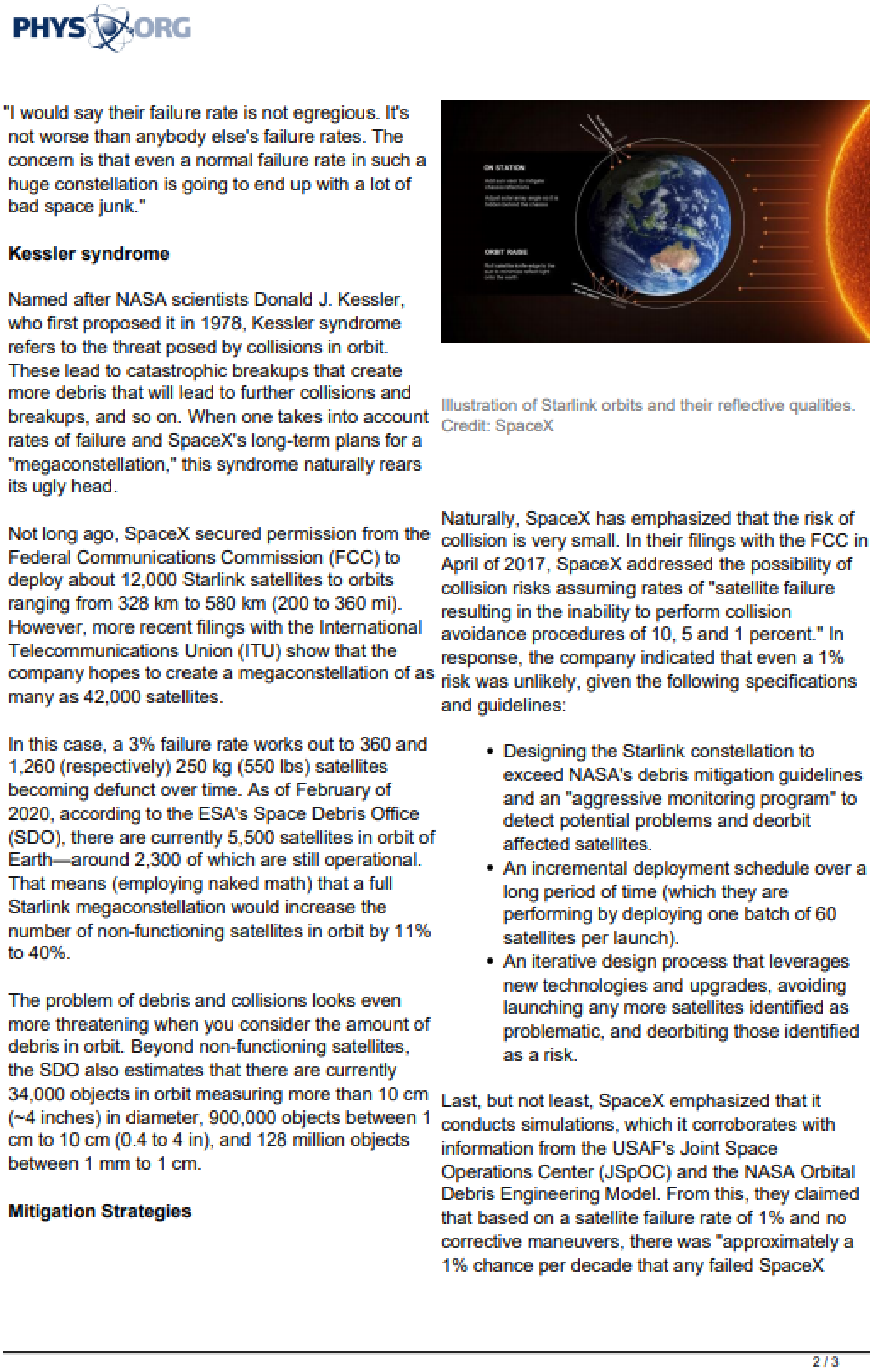


"I would say their failure rate is not egregious. It's not worse than anybody else's failure rates. The concern is that even a normal failure rate in such a huge constellation is going to end up with a lot of bad space junk."

Kessler syndrome

Named after NASA scientists Donald J. Kessler, who first proposed it in 1978, Kessler syndrome refers to the threat posed by collisions in orbit. These lead to catastrophic breakups that create more debris that will lead to further collisions and breakups, and so on. When one takes into account rates of failure and SpaceX's long-term plans for a "megaconstellation," this syndrome naturally rears its ugly head.

Not long ago, SpaceX secured permission from the Federal Communications Commission (FCC) to deploy about 12,000 Starlink satellites to orbits ranging from 328 km to 580 km (200 to 360 mi). However, more recent filings with the International Telecommunications Union (ITU) show that the company hopes to create a megaconstellation of as many as 42,000 satellites.

In this case, a 3% failure rate works out to 360 and 1,260 (respectively) 250 kg (550 lbs) satellites becoming defunct over time. As of February of 2020, according to the ESA's Space Debris Office (SDO), there are currently 5,500 satellites in orbit of Earth—around 2,300 of which are still operational. That means (employing naked math) that a full Starlink megaconstellation would increase the number of non-functioning satellites in orbit by 11% to 40%.

The problem of debris and collisions looks even more threatening when you consider the amount of debris in orbit. Beyond non-functioning satellites, the SDO also estimates that there are currently 34,000 objects in orbit measuring more than 10 cm (~4 inches) in diameter, 900,000 objects between 1 cm to 10 cm (0.4 to 4 in), and 128 million objects between 1 mm to 1 cm.

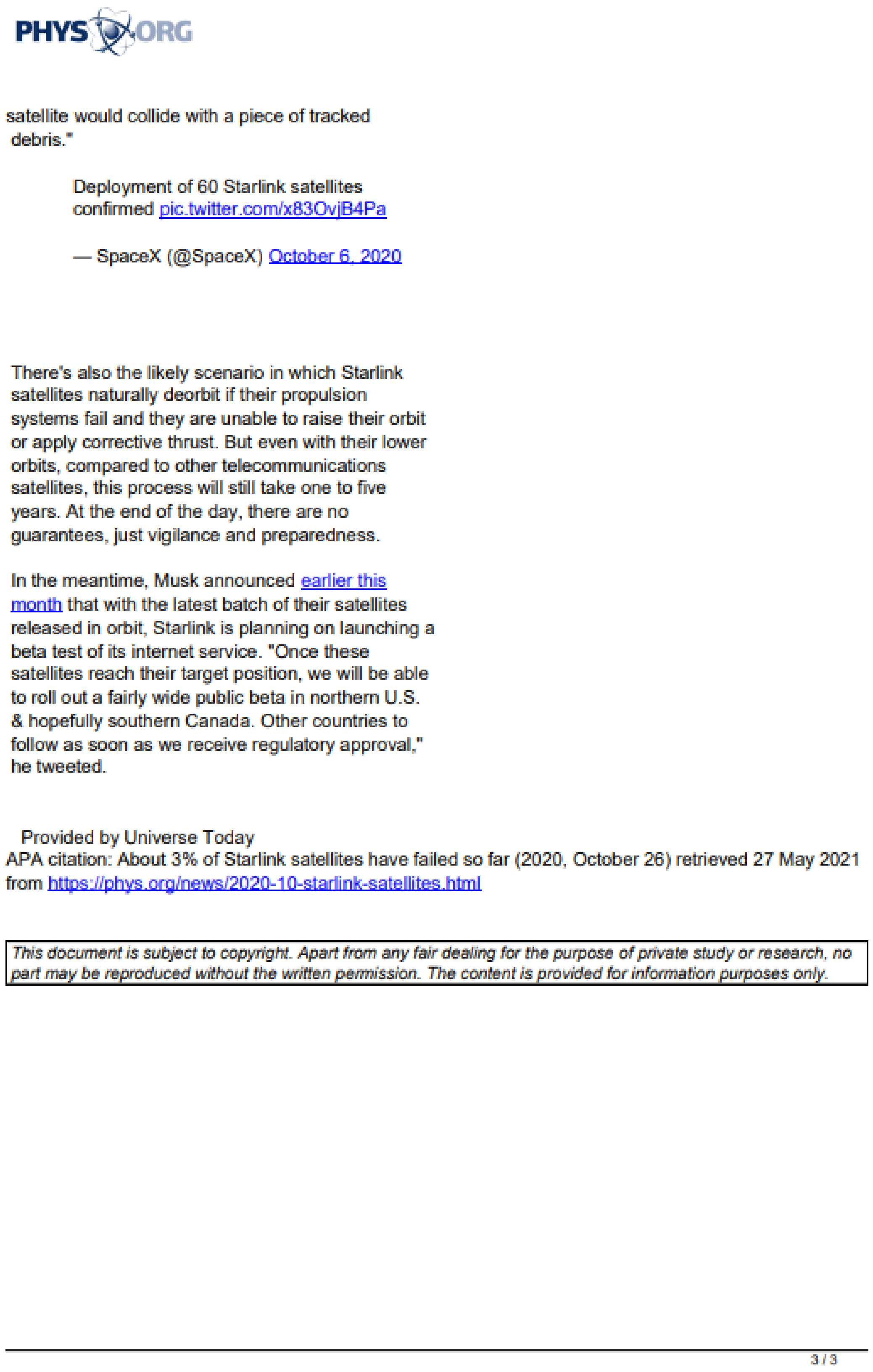
Mitigation Strategies

Illustration of Starlink orbits and their reflective qualities. Credit: SpaceX

Naturally, SpaceX has emphasized that the risk of collision is very small. In their filings with the FCC in April of 2017, SpaceX addressed the possibility of collision risks assuming rates of "satellite failure resulting in the inability to perform collision avoidance procedures of 10, 5 and 1 percent." In response, the company indicated that even a 1% risk was unlikely, given the following specifications and guidelines:

- Designing the Starlink constellation to exceed NASA's debris mitigation guidelines and an "aggressive monitoring program" to detect potential problems and deorbit affected satellites.
- An incremental deployment schedule over a long period of time (which they are performing by deploying one batch of 60 satellites per launch).
- An iterative design process that leverages new technologies and upgrades, avoiding launching any more satellites identified as problematic, and deorbiting those identified as a risk.

Last, but not least, SpaceX emphasized that it conducts simulations, which it corroborates with information from the USAF's Joint Space Operations Center (JSpOC) and the NASA Orbital Debris Engineering Model. From this, they claimed that based on a satellite failure rate of 1% and no corrective maneuvers, there was "approximately a 1% chance per decade that any failed SpaceX



satellite would collide with a piece of tracked debris."

> Deployment of 60 Starlink satellites confirmed pic.twitter.com/x83OvjB4Pa
>
> — SpaceX (@SpaceX) October 6, 2020

There's also the likely scenario in which Starlink satellites naturally deorbit if their propulsion systems fail and they are unable to raise their orbit or apply corrective thrust. But even with their lower orbits, compared to other telecommunications satellites, this process will still take one to five years. At the end of the day, there are no guarantees, just vigilance and preparedness.

In the meantime, Musk announced earlier this month that with the latest batch of their satellites released in orbit, Starlink is planning on launching a beta test of its internet service. "Once these satellites reach their target position, we will be able to roll out a fairly wide public beta in northern U.S. & hopefully southern Canada. Other countries to follow as soon as we receive regulatory approval," he tweeted.

Provided by Universe Today
APA citation: About 3% of Starlink satellites have failed so far (2020, October 26) retrieved 27 May 2021 from https://phys.org/news/2020-10-starlink-satellites.html

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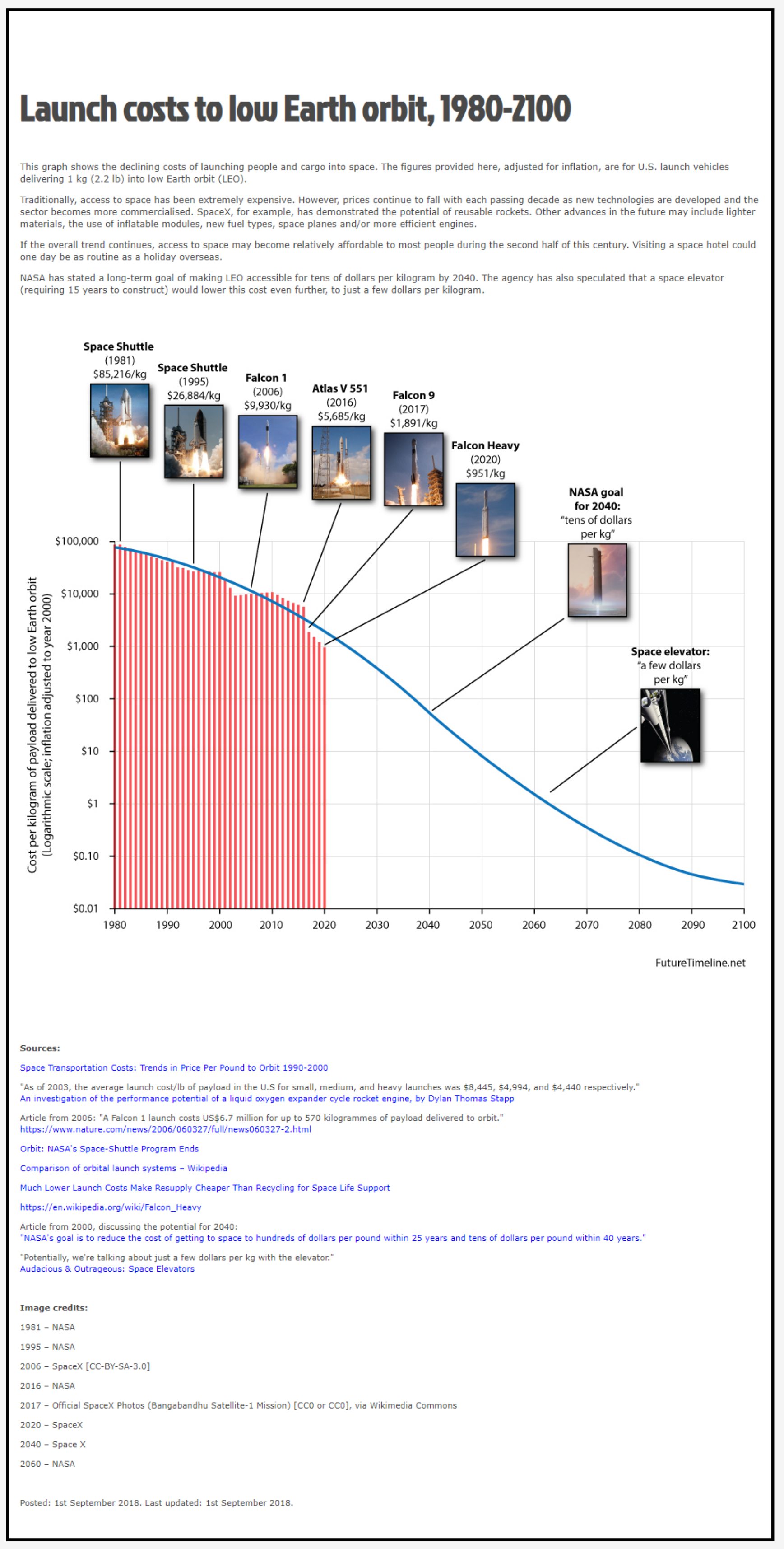

Launch costs to low Earth orbit, 1980-2100

This graph shows the declining costs of launching people and cargo into space. The figures provided here, adjusted for inflation, are for U.S. launch vehicles delivering 1 kg (2.2 lb) into low Earth orbit (LEO).

Traditionally, access to space has been extremely expensive. However, prices continue to fall with each passing decade as new technologies are developed and the sector becomes more commercialised. SpaceX, for example, has demonstrated the potential of reusable rockets. Other advances in the future may include lighter materials, the use of inflatable modules, new fuel types, space planes and/or more efficient engines.

If the overall trend continues, access to space may become relatively affordable to most people during the second half of this century. Visiting a space hotel could one day be as routine as a holiday overseas.

NASA has stated a long-term goal of making LEO accessible for tens of dollars per kilogram by 2040. The agency has also speculated that a space elevator (requiring 15 years to construct) would lower this cost even further, to just a few dollars per kilogram.

FutureTimeline.net

Sources:

Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000

"As of 2003, the average launch cost/lb of payload in the U.S for small, medium, and heavy launches was $8,445, $4,994, and $4,440 respectively."
An investigation of the performance potential of a liquid oxygen expander cycle rocket engine, by Dylan Thomas Stapp

Article from 2006: "A Falcon 1 launch costs US$6.7 million for up to 570 kilogrammes of payload delivered to orbit."
https://www.nature.com/news/2006/060327/full/news060327-2.html

Orbit: NASA's Space-Shuttle Program Ends

Comparison of orbital launch systems – Wikipedia

Much Lower Launch Costs Make Resupply Cheaper Than Recycling for Space Life Support

https://en.wikipedia.org/wiki/Falcon_Heavy

Article from 2000, discussing the potential for 2040:
"NASA's goal is to reduce the cost of getting to space to hundreds of dollars per pound within 25 years and tens of dollars per pound within 40 years."

"Potentially, we're talking about just a few dollars per kg with the elevator."
Audacious & Outrageous: Space Elevators

Image credits:

1981 – NASA

1995 – NASA

2006 – SpaceX [CC-BY-SA-3.0]

2016 – NASA

2017 – Official SpaceX Photos (Bangabandhu Satellite-1 Mission) [CC0 or CC0], via Wikimedia Commons

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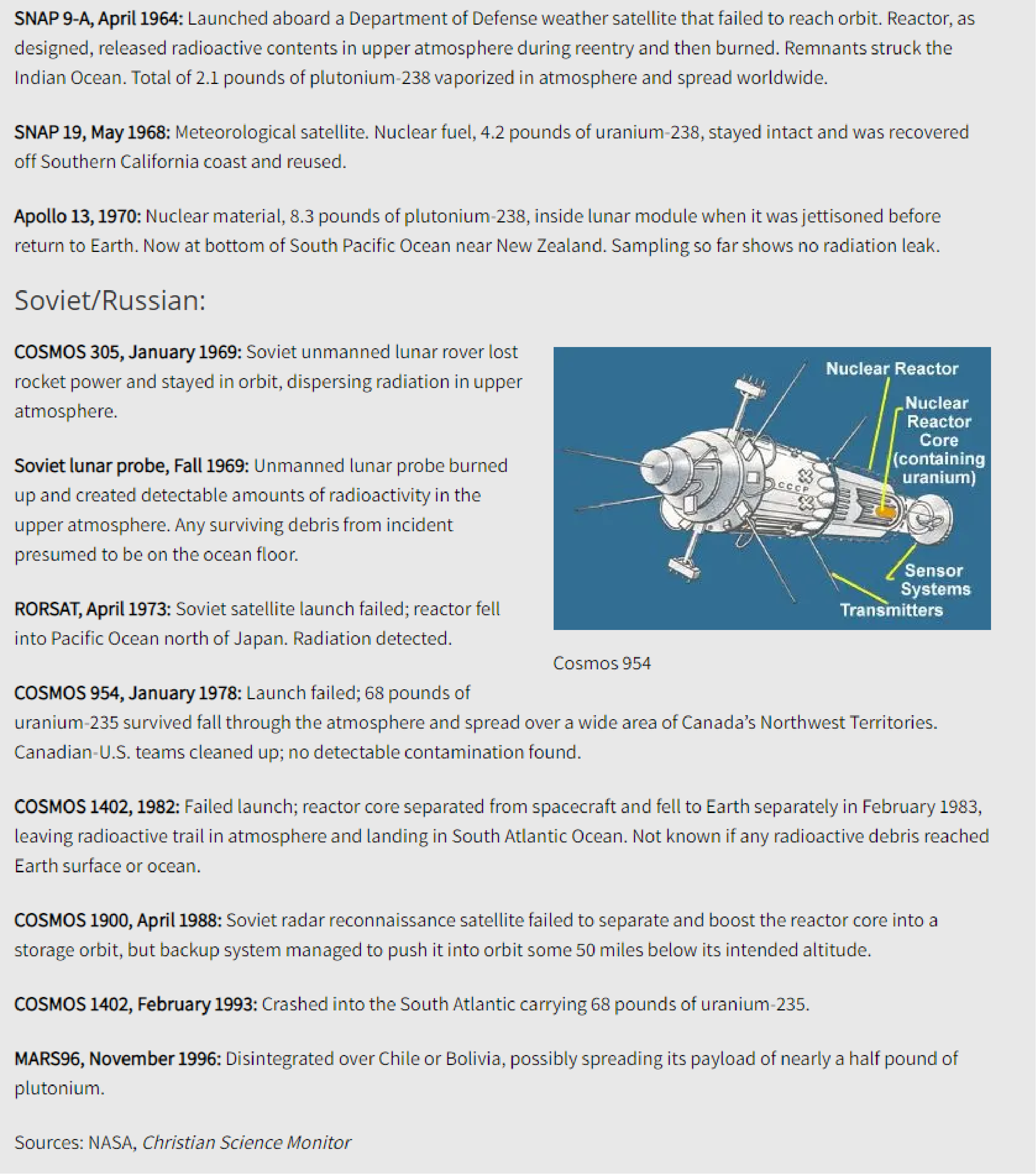

SNAP 9-A, April 1964: Launched aboard a Department of Defense weather satellite that failed to reach orbit. Reactor, as designed, released radioactive contents in upper atmosphere during reentry and then burned. Remnants struck the Indian Ocean. Total of 2.1 pounds of plutonium-238 vaporized in atmosphere and spread worldwide.

SNAP 19, May 1968: Meteorological satellite. Nuclear fuel, 4.2 pounds of uranium-238, stayed intact and was recovered off Southern California coast and reused.

Apollo 13, 1970: Nuclear material, 8.3 pounds of plutonium-238, inside lunar module when it was jettisoned before return to Earth. Now at bottom of South Pacific Ocean near New Zealand. Sampling so far shows no radiation leak.

Soviet/Russian:

COSMOS 305, January 1969: Soviet unmanned lunar rover lost rocket power and stayed in orbit, dispersing radiation in upper atmosphere.

Soviet lunar probe, Fall 1969: Unmanned lunar probe burned up and created detectable amounts of radioactivity in the upper atmosphere. Any surviving debris from incident presumed to be on the ocean floor.

RORSAT, April 1973: Soviet satellite launch failed; reactor fell into Pacific Ocean north of Japan. Radiation detected.

Cosmos 954

COSMOS 954, January 1978: Launch failed; 68 pounds of uranium-235 survived fall through the atmosphere and spread over a wide area of Canada's Northwest Territories. Canadian-U.S. teams cleaned up; no detectable contamination found.

COSMOS 1402, 1982: Failed launch; reactor core separated from spacecraft and fell to Earth separately in February 1983, leaving radioactive trail in atmosphere and landing in South Atlantic Ocean. Not known if any radioactive debris reached Earth surface or ocean.

COSMOS 1900, April 1988: Soviet radar reconnaissance satellite failed to separate and boost the reactor core into a storage orbit, but backup system managed to push it into orbit some 50 miles below its intended altitude.

COSMOS 1402, February 1993: Crashed into the South Atlantic carrying 68 pounds of uranium-235.

MARS96, November 1996: Disintegrated over Chile or Bolivia, possibly spreading its payload of nearly a half pound of plutonium.

Sources: NASA, *Christian Science Monitor*

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CONFIGURE YOUR MISSION

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BASE PRICE ESTIMATE $1,200,000

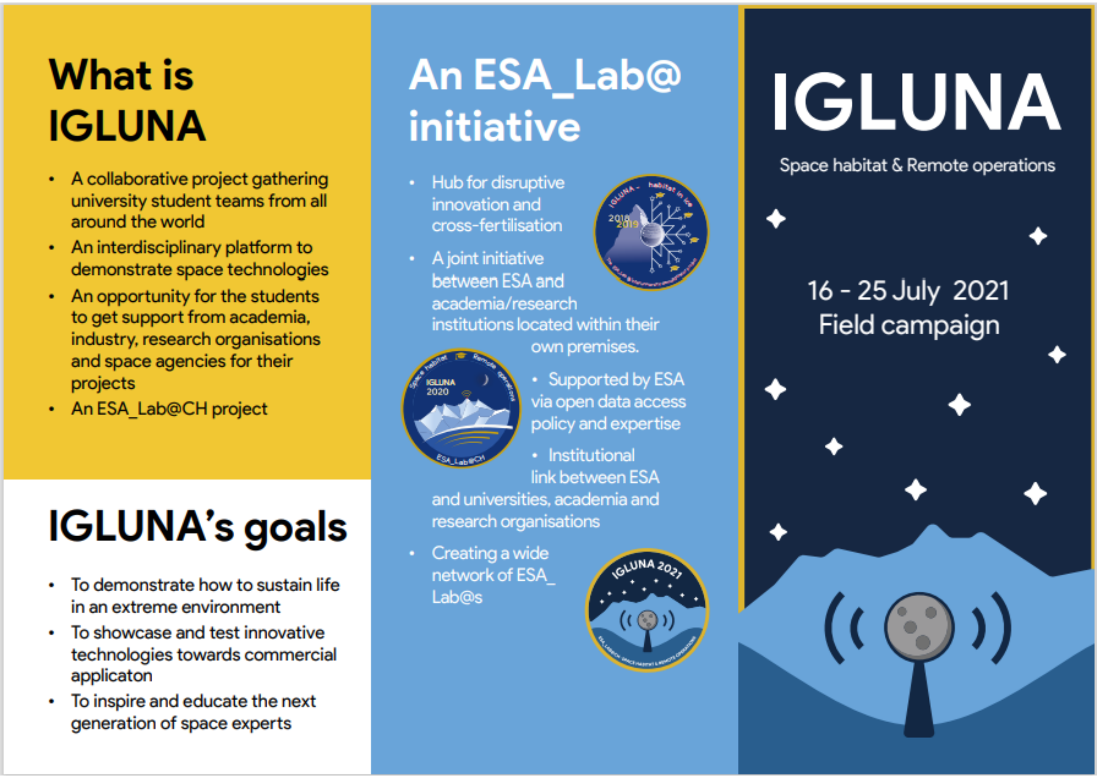
Land on Lunar Surface base price: $1.2M

+ Initial communication allotment: 10 kbps

+ Initial power allotment: 0.5 watts

1 PAYLOAD TYPE

Reference [252] https://space-innovation.ch/wp-content/uploads/2021/06/General-IGLUNA-Flyer_2021.pdf



What is IGLUNA

- A collaborative project gathering university student teams from all around the world
- An interdisciplinary platform to demonstrate space technologies
- An opportunity for the students to get support from academia, industry, research organisations and space agencies for their projects
- An ESA_Lab@CH project

IGLUNA's goals

- To demonstrate how to sustain life in an extreme environment
- To showcase and test innovative technologies towards commercial applicaton
- To inspire and educate the next generation of space experts

An ESA_Lab@ initiative

- Hub for disruptive innovation and cross-fertilisation
- A joint initiative between ESA and academia/research institutions located within their own premises.
  - Supported by ESA via open data access policy and expertise
  - Institutional link between ESA and universities, academia and research organisations
- Creating a wide network of ESA_Lab@s

IGLUNA

Space habitat & Remote operations

16 - 25 July 2021
Field campaign

IGLUNA 2021 :

- Based on the heritage of IGLUNA 2019 and 2020
- 12 teams
- 9 countries
- 220 students
- 1 space habitat with remote control operations
- 1 year project

- 9 days of Field Campaign in Lucerne, Switzerland
- 16-25 July 2021
- Technology demonstration on the Mount Pilatus and dedicated exhibition and control room at the Verkehrshaus - Swiss Museum of Transport

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